<u>Concept Exploration for a Novel Submarine Concept Using Innovative Computer-Based Research Approaches and Tools</u>

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Submitted for the Degree of Doctor of Philosophy

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2016

<u>Declaration</u>

I, Iain Matthew Purton confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Date:

ABSTRACT

The concept of an Unmanned Underwater Vehicle (UUV) "Mothership" submarine (designated Submersible Ship Host (Nuclear), SSH(N)) has already been explored at UCL using the Design Building Block approach by Pawling and Andrews (2011). This thesis builds upon that study, further investigating the design of a large mother-ship submarine. The incorporation of a novel technology such as UUVs into submarines suggests that the traditional evolutionary approach to concept exploration for new submarine designs is questionable. A novel approach to exploring, within the design solution space, novel SSH(N) concepts has been investigated in this thesis.

The significance of incorporating UUVs into submarine design has been explored by conducting an Operational Analysis (OA) of the mix of UUVs required supporting a range of scenarios. This OA gave a coherent justification for a mixed and significant total displacement of UUVs as the main payload for SSH(N)s. A MATLAB computer program, Submarine Preliminary Exploration of Requirements by Blocks (SUPERB), has been produced to generate and assess submarine concept designs. SUPERB also uses a novel generic arrangement approach called, "Compartment X-Listing", which systematically allocates compartments within the pressure hull and then compares individual concept-level submarine designs to typical existing arrangements. Validation of SUPERB and Compartment X-Listing is presented and discussed using two existing submarine designs and two radical concept design proposals.

A novel approach of modifying a nominal Pareto Front representation for complex novel designs called the Notional Pareto Front (NPF) has been used with SUPERB to generate designs and is considered to be an innovation in marine design practice. The NPF approach seeks to bound the solution space and focus concept exploration on a smaller region. This is seen to have the potential to inform an extensive early stage exploration of the design solution space, as a research approach for future concept level investigations, such as for SSH(N)s. Recommendations are made as to how this design approach may be taken forward.

ACKNOWLEDGEMENT

The infinite support and patience of my friends, family, and better half, Florence, without whom this thesis would not have been written.

The guidance of the Design Research Centre research group at UCL and, in particular, Prof. David Andrews and Dr Rachel Pawling.

Funding for the Ph.D. research concerning this thesis was partly provided by Babcock International, whose support is gratefully acknowledged and partly by UCL Impact Studentship.

CONTENTS

NOMENCLATURE

A	Bluff body area of a UUV [m^2]
AAW	Anti-Aircraft Warfare
AIAA	American Institute of Aeronautics and Astronautics
ARM	Availability, Reliability and Maintenance
ASM	Anti-Ship Missile
ASNE	American Society of Naval Engineers
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
BG	Distance between a Submarine's Buoyancy and Gravity Centroids [m]
c	Constant
C2	Command and Control
C_d	Coefficient of Drag
CFD	Computational Fluid Dynamics
CISE	Computer Information Science and Engineering
CONOPs	Concept of Operations
CPU	Central Processing Unit
DARPA	Defense Advanced Research Projects Agency (Agency of the Dept. of Defense in the United States of America)
DBB	Design Building Block (UCL Designation for Design Component in an architecturally driven design method)
DDD	Deep Diving Depth [m]
DRC	Design Research Centre (Research team in Marine Research Group in the Dept. of Mechanical Engineering, University College London)
EMINT	Electromagnetic Intelligence
ET	Endurance Time (Hours) (Time a UUV is On-Station, See USGOT in Chapter 3)
E_{Total}	Total energy stored onboard a UUV [Joules]
F	Force
$\vec{F}$	Force Vector
FEA	Finite Element Analysis
GJ	Gigajoule [Energy]
GM	The Vertical Distance between a Ship's Centre of Gravity and Metacentre [m]
GUI	Graphical User Interface
HGA-MAS	Hybrid Genetic Algorithm Multi-Agent System (A type of Genetic Algorithm)
HWT	Heavyweight Torpedo
ICBM	Intercontinental Ballistic Missile
IEEE	Institute of Electrical and Electronics Engineers (USA)
IKL	Ingenieur Kontor Lübeck (A German defence company responsible for SSK submarine design)
IMarE	The Institute of Marine Engineering
IMarEST	The Institute of Marine Engineering, Science and Technology
IMDC	International Marine Design Conference (Triennial)
IR	Indiscretion Ratio [%] (Ratio of time engines are atmosphere-aspirated (snorting) to total transit time)
ISR	Intelligence, Surveillance and Reconnaissance
ISSMO	International Society for Structural and Multidisciplinary Optimisation
ITTC	International Towing Tank Conference

k	Stiffness of a spring
K_1	Collection of terms that have been repeated on multiple occasions in the whole equation for USGOT's "Payload Calculator"
L	Limit: The Probabilistic Limit at which the detection of a target is at satisfactorily high level of confidence. 95% is used for all simulations in this research.
LAR	Launch and Recovery
LARS	Launch and Recovery System (Usually for small vehicles from a larger vessel)
LR	Loss Rate (of UUVs Performing a Mission)
L_{UUV}	Length of an MUV/UUV [m]
MCM	Mine Countermeasures
MIT	Massachusetts Institute of Technology (Located Cambridge, Mass., USA)
MOD	Ministry of Defence (UK)
MOE	Measure of Effectiveness
MOP	Measure of Performance
MoTPC	Measure of Tradable Performance Characteristics (Defined in text for purposes of this research, see Appendix E)
MT	Maintenance Time [Hours] (Time a UUV takes for recharging, maintenance and data transfer)
MUV	Manned Underwater Vehicle
n	Number of (Real) Nodes in a Polygon Set
NAME	Naval Architecture and Marine Engineering (A part of UCL's Mechanical Engineering Department)
Num_{ST}	Number of Steam Turbines (For a submarine's propulsion)
Num_{TG}	Number of Turbo-Generators (For a submarine's propulsion)
NPF	Notional Pareto Front (See Chapter 6)
N_s	Total Number of UUVs on station (for that UUV Category)
N_T	Total Number of UUVs (for that UUV Category)
N_{UUV}	Number of UUVs Recharging/Refuelling (for that UUV Category)
OA	Operations Analysis
OPV	Offshore Patrol Vessel (A type of naval ship)
PA	Packing Algorithm (Produced by van Oers (2011) for generating ship arrangements, See Chapter 4)
PH	Pressure Hull (of a submarine)
PL&C	Physically Large and Complex System
$POWER_{DG}$	Generated Power of Diesel Generator [MW]
$POWER_{RC}$	Generated Power of Nuclear Reactor [MW]
RAM	Random Access Memory
RC	Nuclear Reactor Compartment
RINA	Royal Institute of Naval Architects (UK)
RN	Royal Navy
RoB	Reserve of Buoyancy [%] (Describes the buoyancy relative to surface displacement. Typically 10% of surfaced displacement for a military submarine)
ROO	Radius of Operations [nm]
SBD	Set Based Design (A Form of Initial Design Philosophy Created by the Toyota Automobile Company. See Chapter 2)
SCA	Submarine Concept Aid (A submarine initial synthesis design tool produced by Biddell (2000). See Chapter 2)
SEAP	SUPERB's External Arrangement Program (Used to perform the arrangement of equipment externally to the pressure hull(s), see Chapter 4)

SG	System Group (A collection of related submarine systems, see Chapter 6)
SLMM	Submarine Launched Mobile Mine
SNAME	Society for Naval Architects and Marine Engineers (USA)
SRe	Sprint Reserve [%] (Reserve of Energy Stored on a UUV, See Appendix B on USGOT Construction)
SR_n	Sensor Range of Node [nm]
SSBN	Submersible Ship Ballistic Nuclear (Nuclear Powered, Ballistic Missile)
SSC	Ship-to-Shore Connector (United States Navy ship for amphibious operations)
SSGN	Submersible Ship Guided Nuclear (Nuclear Powered, Guided Missile)
SSGT	Submersible Ship Gas Turbine (Gas Turbine Powered) (Concept submarine by BMT, See Chapter 5)
SSH	Submersible Ship Host (Conventionally Powered, UXV Mothership)
SSHN	Submersible Ship Host Nuclear (Nuclear Powered, UXV Mothership)
SSK	Submersible Ship Killer (Conventionally Powered)
SSKN	Submersible Ship Killer (Nuclear Powered) (See Chapter 5)
SSN	Submersible Ship (Nuclear Powered) (Attack Submarine)
SST	Submersible Ship Teleport (A Hypothetical vessel proposed by the candidate, See Chapter 5)
ST&C	Standard Trim and Compensation Condition See Chapter Appendix 3 of Burcher & Rydill (1994)
SUPERB	Submarine Preliminary Exploration of Requirements by Blocks (A submarine initial synthesis design tool produced by the candidate. See Chapter 4)
TD	Transit Distance [nm]
TD_{max}	Maximum Transit Distance [nm]
TD_{min}	Minimum Transit Distance [nm]
TLAM	Tomahawk Land Attack Missile (Submarine launched variant of an American cruise missile. Launched from either a torpedo tube of a Vertical Launch System)
TLIV	Top-Level Input Variable (For SUPERB)
TrT	Transit Time [Hours]
TS	Transit Speed [Knots]
TS_{max}	Maximum Transit Speed [Knots]
TS_{min}	Minimum Transit Speed [Knots]
TS_{opt}	Transit Speed to achieve maximum UUV range [Knots]
u	Displacement squared of a node in the spatial vector: x (See Notes on USGOT Construction in Appendix B)
U	Submarine Velocity [Knots]
UAV	Unmanned Aerial Vehicle
UCL	University College London
UDT	Underwater Defence Technology (International Conference)
$\vec{U}$	Displacement Vector (For Nodes in an FEA Mesh)
U_{Esc}	Escape Velocity on Battery Power Only [Knots]
UGV	Unmanned Ground Vehicle
USGOT	UUV Sensor Grid Optimisation Tool (An operational analysis tool produced by the candidate, see Chapter 3)
USN	United States Navy
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UXO	Unexploded Ordinance
UXV	Unmanned ‘X’ Vehicle (Any unmanned vehicle)

VD	UUV Displacement [kg] (UUV displacement typically quoted in kilograms and not tonnes)
VN	Virtual Node (Virtual 'UUV') in effect a 'source' of probability.
α	Ratio between Transit Speed and Optimum Speed for Maximum Range
x	Spatial vector
$\eta_{Propulsor}$	Efficiency of a Submarine's Propulsor [%] (Combined mechanical and hydrodynamic efficiency)
Φ	Product of the number of UUVs on-stations (of that type of UUV) and the transit distance (TD) (See USGOT in Chapter 3)

FIGURES

TABLES

CHAPTER 1 - INTRODUCTION AND BACKGROUND

1.1 BACKGROUND TO SUBMARINE AQUISITION

The distribution of submarines around the globe is such that the major (first tier) navies (e.g. Royal Navy, US Navy) are building fewer but more expensive and larger boats in the face of budgetary pressures and increasing capabilities. The end of the Cold War produced the "Peace Dividend", which was a political driver to reduce defence spending in major Western nations and redistribute the public money saved to other public services (Intriligator, 2010). Other sectors of major Western governments government spending, such as healthcare, have their financial inertia (Kirkpatrick & Pugh, 1985) and it is not always politically viable to redirect funding back towards defence. This pressure on the defence budget of a first tier nation is illustrated in Figure 1 for UK defence spending, which has decreased as a share of GDP since the early-1980s.

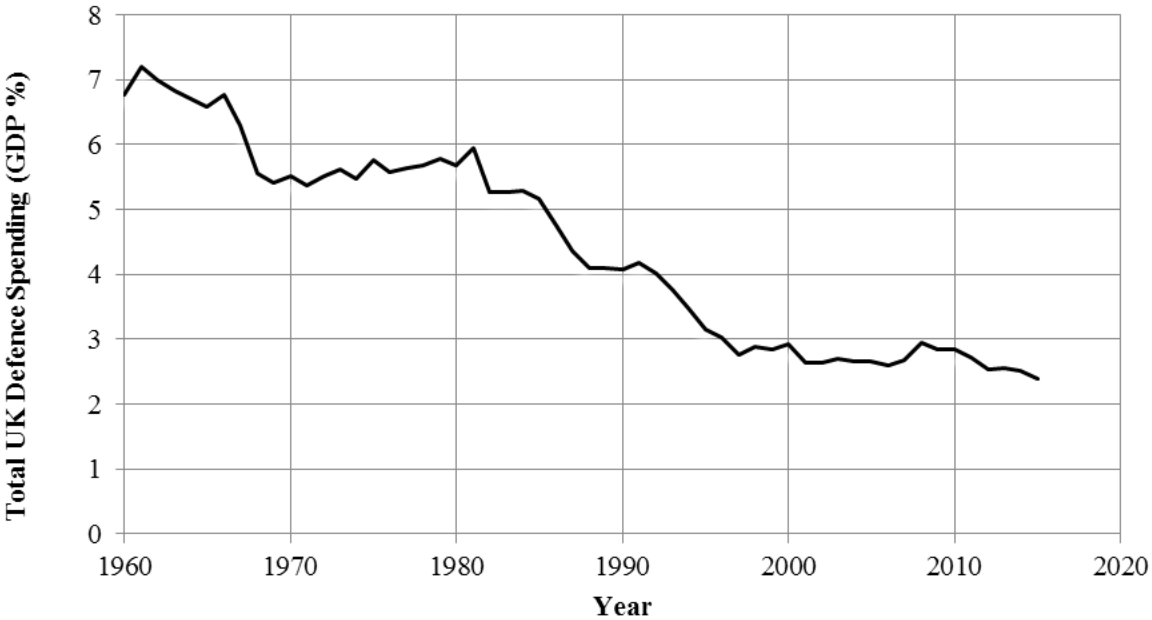

Figure 1 – Defence Funding for the UK (UK Public Spending, 2015)

Conversely, second tier navies (e.g. Indonesia and Pakistan), are obtaining (relatively) cheaper and smaller boats that are considered quite capable. Often these boats are bought exported/manufactured under licence from first tier nations. An example of such a purchase is the export of Germany's highly successful Type 209 to the South African Navy (IT Web, 2008). Some ambitious second-tier navies are developing their own submarines. For example, India is currently upgrading their navy's Nuclear Attack Submarines (SSNs) and nuclear-powered ballistic missile submarines (SSBNs) (Mazumdaru, 2015) and Brazil has a programme to acquire SSNs (James Martin Center, 2015).

Table 1 shows that second tier navies, such as North Korea (rank 2 by unit numbers) often have more submarines than first tier navies[1] such as France (rank 13 by unit numbers), however, pure numbers are misleading. In North Korea's case, most of its boats are midget submarines (less than 150 tonnes submerged displacement), which are completely incomparable to larger ocean-going submarines. Furthermore, the North Korean submarines are mostly obsolete (Gady, 2015). To differentiate between modern boats that are sufficiently large for ocean-based operations small or obsolete submarines typical of second tier navies, Table 1 also shows the number of submarines each nation possesses and have been commissioned post-Cold War (after 1989) plus are larger than 2,000 tonnes. Thus, first-tier navies, such as Japan, have a high proportion of their submarine fleet, that are large and modern (100%); in contrast, Iran can only field a small percentage (~10%) of such submarines in its fleet.

Table 1 – Global Submarine Fleets

Rank by Total	Country	**Total Number of Submarines** (Global Fire Power, 2015)	Modern Large Submarines [2,3]
1	USA	72	48
2	North Korea	70	0
3	China	67	46
4	Russia	55	43
5	Iran	32	3
6	Japan	16	16
7	India	15	6
8	South Korea	13	1
9	Turkey	13	0
10	Columbia	11	0
11	Greece	11	0
12	UK	10	8
13	France	10	6
14	Pakistan	8	3
15	Indonesia	6	0

[1] Defined as a submarine fleet comprising of >50% modern large submarines, as per the definition used in this thesis.
[2] Commissioned 1989 or later and greater than 2,000 tonnes submerged displacement
[3] Table 1 has been constructed by combining data from the open sources in December 2015.

As well as the raw numbers of units, submarine displacement, cost and capability should be factors in determining the measure of a navy's submarine force. Figure 2 illustrates that the number of Royal Navy attack submarines has dropped since circa 1960, with a significant decline following the end of the Cold War. However, it also indicates that the displacement of the average attack submarine has increased over time. For example, in 1980, the average displacement of a Royal Navy attack submarine was about 3,400 tonnes per submarine but, in 2010, it was some 5,500 tonnes per submarine. Similarly, the cost (Unit Production Cost[1]) for a submarine had gone up for first-tier navies.

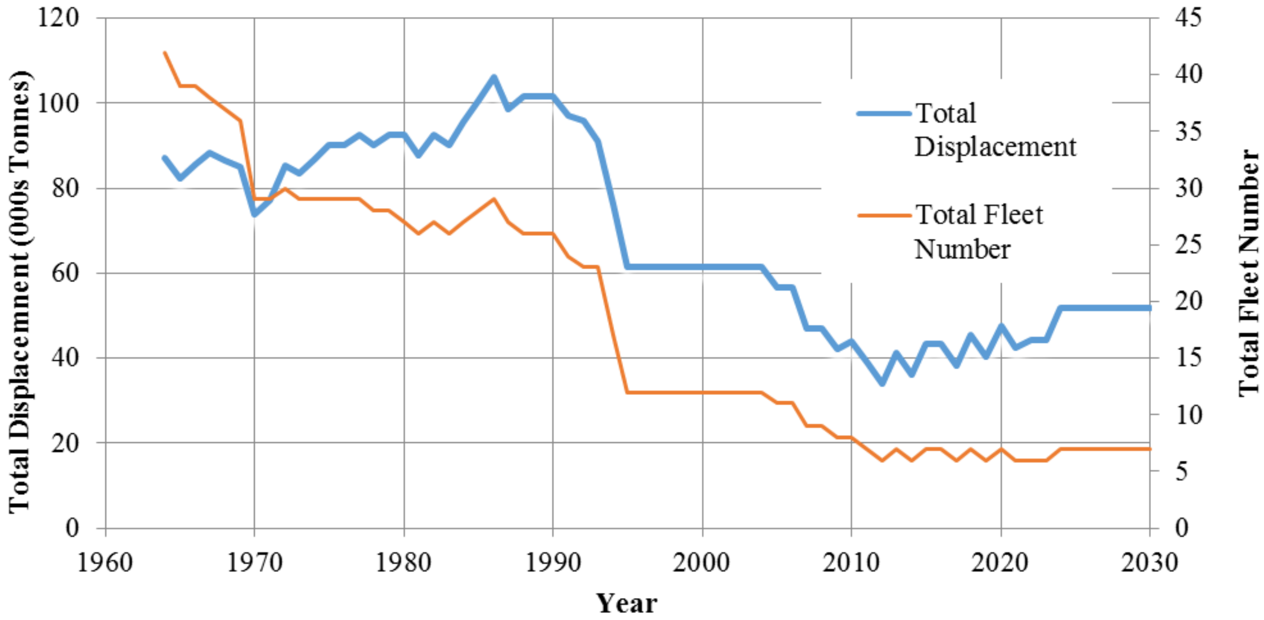

Figure 2 – Royal Navy Total Attack Submarine Displacement over Time[2]

It has been suggested that the latest Royal Navy (RN) SSN (*Astute*-class) boat cost £1.2 billion to deliver (Naval-Technology.com, 2014c), while its predecessor; the 5,300 tonne Trafalgar-class (Jane's Fighting Ships, 1987) cost the equivalent (inflation adjusted) £575 million. It has also been estimated that the larger 7,400 tonne Astute-class carries 50% more weapons[3] (Naval-Technology.com, 2014c), which can be considered a crude measure of capability. This comparison carries greater weight due to both classes being similar in role and style

[1] The Unit Production Cost (UPC) is the averaged expenditure (both fixed and variable) to construct but not operate each unit. (Accounting Tools, 2012)
[2] Data gathered by candidate from various open sources in December 2015.
[3] Weapons in this context refers to all ordinance carried. Both the *Trafalgar* and *Astute* classes carry torpedoes and land-attack missiles.

of design. This style in an orthodox style of design which has been prevalent for the last 40 years in the Western world. Existing naval design practices heavily leverage preceding designs resulting in successive iterations of the same style of design (Andrews, 2006). An example of such a successive iteration is the *Astute*-Class. A simplified implication is that for doubling of the cost and a 40% increase in size for a similar style of design, the capability could be considered to have increased by 50%, and hence there are diminishing returns in terms of capability achieved due to the greater increase in the cost of submarine acquisition. It could be inferred from this that a revolutionary change in submarine design is necessary to break this trend.

An increasing asymmetric threat to first tier navies comes from the proliferation of small and relatively cheap conventionally powered hunter-killer submarines (SSKs) by second-tier navies, which are upgrading their current submarine fleets. There is a growing body of thought that considers operations in the littoral (Naval-Technology.com, 2014a) will be the primary focus for submarine operations in the near future and this should be addressed when investigating the next generation of submarines. This emphasis on the littoral arises from increasing asymmetric threats, such as modern SSKs. These SSKs obtain a high level of covertness in this topographically ‘cluttered’ environment – hindering anti-surface and anti-subsurface warfare. SSKs have also in the past tended to be smaller and quieter than similar SSNs (Wrobel, 1985)– giving them an additional advantage. This benefit persists to the modern day (University College London (Adelaide), 2013).

However, there have been suggestions (Naval-Technology.com, 2014a), that future technological advances may reduce the level of stealth a deployed submarine can expect to exercise in the littoral environment – forcing it to operate further away from any threat and thus decreasing its effectiveness.

1.2 UUVS IN SUBMARINES

Unmanned vehicles that operate in different environments (designated UXVs) have been proposed as a means of enhancing the capability of naval vessels (Binns, et al., 2011). Of particular interest for submarine operations is the Unmanned Underwater Vehicle (UUV), since it offers the possibility of undertaking many of the roles traditionally taken by a submarine. The likely need to respond to an increasing number of SSKs operating in theatres across the globe in the coming decades (Development, Concepts and Doctrine Centre, 2010) will provide new operational challenges for submarine operating nations. A UUV payload could be a force multiplier, reducing the operational risks to which the manned submarines would be exposed. UUVs could additionally provide increased capability for undertaking missions such as Intelligence, Surveillance and Reconnaissance and Capital Asset Protection as highlighted by Purton et al. (2013b).

For convenience in investigating the impact of UUVs on submarine design, three types of UUV have been defined for this research. The largest class has been designated “Category A”, which is intended to include vehicles large enough to be manned underwater vehicles (called MUVs) with displacements of 10-20 tonnes. The next class is “Category B”, which are torpedo-like UUVs (such as the Hugin 1000 (Kongsberg, 2012)), which can be launched via submarine torpedo tubes and hence typically have a 21-inch diameter and approximately 1,000 kg displacement. Lastly, there are the “Category C” UUVs, which are typically disposable UUVs, such as radio beacons or countermeasures to homing torpedoes with displacements of some 250 kg and typically 10 inches in diameter. As with the Category B class, the Category C class can be tube launched.

The novel submarines investigated in this thesis are intended to carry, deploy and recover a substantial number of unmanned underwater vehicles (UUVs). This novel submarine concept could be a step change from the traditional hunter-killer submarines, which dominated advanced Western navies during and since the end of the Cold War. This new type of submarine has been designated Submersible Ship Host (Nuclear) (SSH(N)) and would perform missions primarily using its UUV fleet. The ‘Mothership’ idea of a large vessel designed to host smaller children vessels has indeed already been explored in science fiction, with possibly the strongest example in the zeitgeist being “Independence Day” (1996). Indeed, in Japanese, “aircraft carrier” can be literally translated as “aviation Mother-ship”.

Nuclear-powered propulsion is not necessarily a prerequisite but needs to be addressed as a possibility, due to the common use of nuclear power for submarines by first tier navies. The SSH(N) would differ from current and near future submarines, which seek to augment their orthodox designs with a few UUVs, such as the Swedish A26 vessel (Saab, 2015). The idea of an Unmanned Underwater Vehicle (UUV) “Mothership” submarine (i.e. an SSH(N)) has already been explored at UCL (Pawling and Andrews, 2011).

A set of SSHN concepts were presented by Pawling and Andrews (2011), and this formed the starting point for much of the current research. These concept designs for submarines carried a substantial number of UUVs and, importantly, these concept designs are naval architecturally balanced to the usual concept level of definition (i.e. valid). Naval architectural balance is defined as the achievement of several requirements by a submarine design if it is to be considered feasible. These include hydrostatic balance, geometric balance to ensure the submarine is sufficiently dimensioned to contain its contents, and requirements to ensure sufficient powering for supporting the crew and achieving required design speeds.

Pawling and Andrews (2011) discussed new technologies, such as UUVs, to justify investigating radical submarine configurations that break with evolutionary submarine design. They recognised that UUVs provide a possible solution to stealth operations in littoral environments as they could access area currently unattractive to large submarines due to their lack of size. Also, they could possibly be able to cover a wider area than a submarine due to their numbers and lessen the threat to the SSH(N), as it could be placed further away from a threat. In order to achieve these operational aims, a significant number of UUVs was considered to be necessary. It then followed that a vehicle is necessary to transport and support this 'fleet of mixed UUVs' and if this vehicle also needs to be stealthy, then an SSH(N) seemed the likely solution.

1.3 JUSTIFICATION FOR EXPLORING THE UNREFINED SOLUTION SPACE

1.3.1 RATIONALE FOR THE PRODUCTION OF THE REFINED SOLUTION SPACE

A number of special terms are used in the research and are defined in Table 2.

Table 2 - Definition of Specialist Terms used in the Research

"Synthesised"	This term refers to the architectural arrangement of compartments and physical features of a submarine design at a concept level of granularity.
"Preferred"	This term refers to designs deemed attractive by some metric, given all the available information at the concept level of definition.
"Conceivable"	This term refers to concept level designs that could be believably naval architecturally balanced by the end of the design process.
"Unrefined"	This term refers to conceivable and preferred designs, which have not yet been synthesised.
"Valid"	This means that a design is naval architecturally balanced to a conceptual level of granularity
"Refined"	This term refers to valid, synthesised designs.

Andrews (1994) also stated that within concept exploration, all potential solutions should be explored and not rejected by preconceived ideas (based on existing designs), because Requirements Elucidation (Andrews, 2003a) is working out what is wanted, affordable and realistic for a new complex system. "Requirements Elucidation" was coined by Andrews in preference to Requirements Engineering, which Andrews considered prematurely limited. The exploration of radical design options by subjective decisions focussed on devising the requirements functionally without regard to material options necessary to inform on the cost and risk of a set of achievable requirements. Andrews further proposed that requirements for a design should be elucidated using an architectural approach, so whole-boat synthesis is considered during the exploration of design concepts. Andrews (1994) has proposed a three-dimensional space to chart the "Preliminary Design Solution Space". This space would have three principal axes: capability (operation performance), packaging and technology. From the various options in this solution space, concept level design solutions can then be evolved in the subsequent overlapping stages of the Concept Phase (Andrews, 2013) of design, with fidelity increasing for those design solutions that look attractive or explore further aspects advancing Requirements Elucidation. However, the need to naval architecturally balance a submarine, compared to a ship, makes the gathering of knowledge during concept exploration exceptionally important (Nordin, 2014). This helps to ensure that designs subsequently considered in Concept Studies are feasible. Effectively, this implies a greater degree of overlap between the Concept Exploration and Concept Studies stages of the Concept Phase even than was proposed by Andrews (1994). This implies that designs should be as information rich as possible in critical aspects, yet still within the limits of suitability of a concept level of definition.

The candidate has adopted the term "highly uncertain[1]" to describe a problem that does not have sufficient *a priori* knowledge to define a preliminary set of requirements of possible designs to be considered during concept exploration. This could be considered to encompass the inability to locate solutions in Andrews (1994) three-dimensional Preliminary Design Solution Space. If the design problem is highly uncertain, it could also be considered an example of a "wicked problem". The "wicked problem" was defined by Rittel and Webber (1973) and commented on by Andrews (2003a) regarding its applicability to naval vessel design as "*identifying what is the nature of the problem is the main problem, and that attempting to do so without recourse to potential material solutions verges on making a difficult operation impossible.*" Rittel and Webber also remarked that the "*formulation of a 'wicked' problem is the problem…setting up and constraining the solution space… is more essential than the remaining steps of searching for a solution*". This definition highlights the importance of correctly elucidating requirements by exploring the solution space especially for a *highly uncertain* problem, such as the investigation of the SSH(N) concept.

[1] Another term for this type of problem could be *sine examplo* (meaning without example)

An example of a highly uncertain problem would be the design of a potentially radical vessel, such as an SSH(N). While the technology level would be readily known to be high, the design problem could be highly uncertain due to an insufficient definition of the level of packaging (e.g. for a UUV payload) and accompanying unknown capabilities for novel features (e.g. UUVs) given there is unlikely to be any reliable pre-existing concept designs from which to specify the solution.

Nordin (2014) has shown that for a new but ‘evolutionary’ type of submarine, typical of submarine design, concept exploration can be straightforward if the desired capability, technology and packaging are all approximately pre-defined. The SSH(N) concept lacks this definition and is instead similar to the ship examples in Andrews (1994). However, unlike these ship design problems, a greater degree of knowledge is needed for the submarine Concept Phase to ensure naval architectural balance is achievable. It is thus proposed that concept exploration for SSH(N)s be a two-stage process.

Firstly, the refined solution space can be produced by obtaining knowledge into the possible characteristics of solutions. These could include both design characteristics, such as submerged displacement and top speed, and emergent properties, both performance-related, such as seakeeping and “Style”[1] (Brown & Andrews (1980)). This could be considered the exploration of the solution space to find solution locations in Andrews (1994) three-dimensional Preliminary Design Solution Space. This stage has been termed “production of the refined solution space”. The following second stage of concept exploration would be ‘conventional’ (for submarines) concept exploration. This second stage has been performed by Nordin (2014).

1.3.2 SOLUTION SPACE DEFINITION

The abstract solution space, which design solutions inhabit, must be defined in preparation for outlining the scope of this research. In a discussion between Andrews and Purton (2015) a particular abstract design space was considered to be one in which all unrefined potential designs could be described visually, linguistically and numerically. This space has been termed the “unrefined solution space” by the candidate. These unrefined potential solutions are not designs but sufficient listings of submarine material characteristics necessary to evolve concept solutions, which are subsequently checked by synthesis to a) meet a set of (preliminary) requirements, and b) be balanced at the concept level.

[1] Style is explained later in Subsection 2.4.2

The limit of the unrefined solution space is the designer's creativity in generating solutions to meet perceived and ill-defined requirements. A portion of the unrefined solution space could, following the synthetisation of unrefined potential solutions into balanced concept designs, be divided and isolated to define the "refined solution space". This process has been termed "production of the refined solution space" in this research, as it is intended to be performed to facilitate 'conventional' concept exploration, from which to perform Requirements Elucidation (Andrews, 2013) of a design solution. The refined solution space contains synthesised and naval architecturally balanced designs (to a conceptual level of definition) which are of interest to the designer. Both the refined and unrefined solution spaces are both considered types of solution space. Furthermore, in both solution spaces a Pareto front[1] can be constructed and these are used in the research.

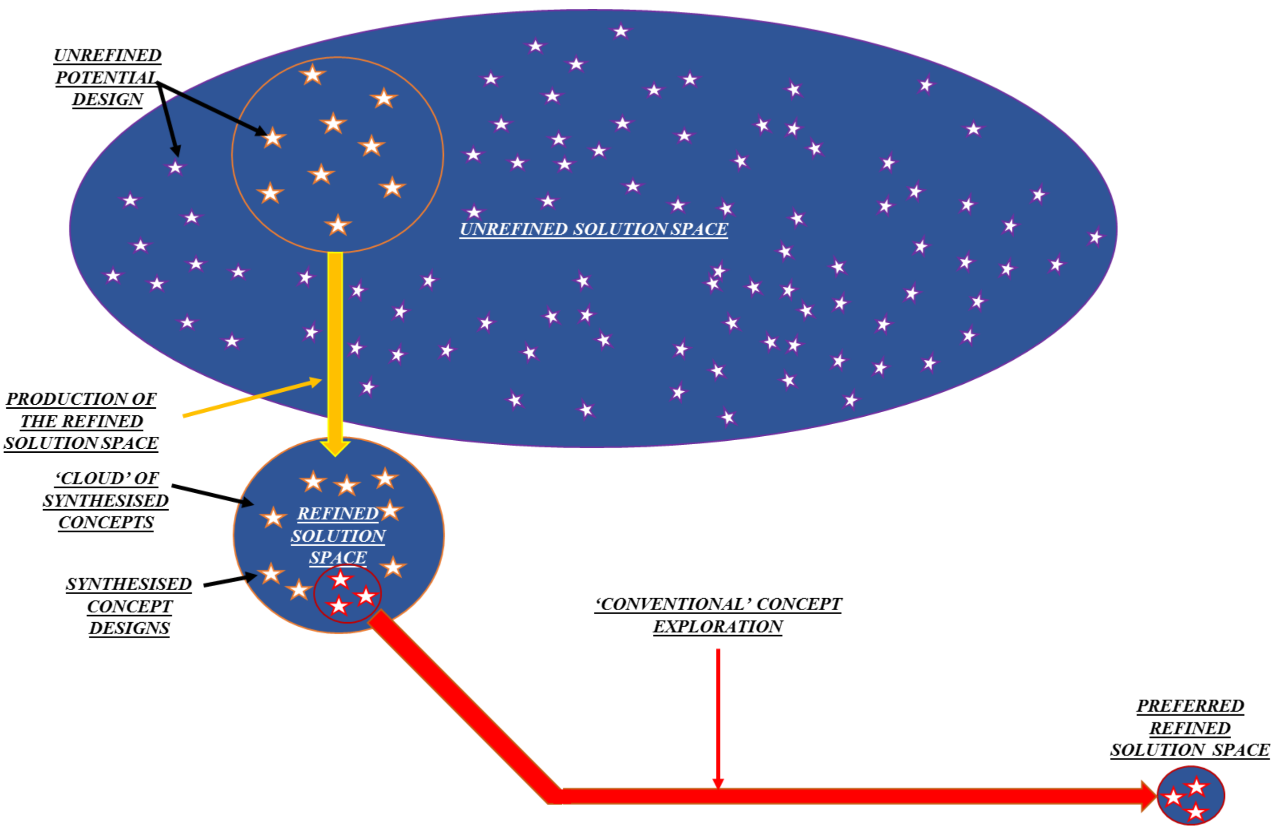

Figure 3 – Illustration of the Definition of the Solution Space

The refined solution space can be considered as a cluster or series of clusters of fuzzily defined 'clouds' of balanced concept designs. A cloud (shown in Figure 3) can be considered a set of solutions that contain similar

[1] A Pareto front of is a front design options for which a superior performance cannot be achieved which additional cost.

characteristics and so has the same approximate location in Andrews' (1994) Preliminary Design Solution Space. Thus, a cloud represents an option to solve the design problem, and it is possible for multiple clouds to exist (not shown Figure 3). These clouds can be explored to understand design trade-offs in concept exploration, from which requirements can be defined, by the approaches proposed by Andrews (1994) and Tibbitts and Keane (1995).

Concept exploration should also to establish a "preferred refined solution space" from which Concept Studies stage of the Concept Phase (Andrews, 2013) could be subsequently undertaken. This could be achieved by increasing the fidelity of the design. Solutions could then be identified in the preferred refined solution space. The preferred refined solution space can be considered as tightly bound clusters of concepts within the aforementioned clouds. The preferred refined solution space then contains the design solutions that come out of the concept exploration process and put forward for subsequent concept studies. Andrews' (1994) approach to the Concept Phase has a final stage (called Concept Design) to provide the definition to enable the Feasibility Phase. In the Concept Design, a preferred solution design is 'worked up' with trade-offs, cost, capability and design risks explored by the generation of design options from the selected baseline.

1.4 SCOPE

Performing an actual concept exploration for the exploration of the SSH(N) idea is outside the scope of the research. This thesis in an investigation into the research approaches and tools which could help facilitate such an exploration. This research does this by simulating a production of the refined solution space for SSH(N)s.

This thesis is only concerned with the investigation of the SSH(N) concept for military purposes. Furthermore, it is focussed on ocean going (i.e. larger) SSH(N)s, which are comparable to modern vessels. The technology used in SSH(N) designs considered in this thesis is intended to be modern and conceivable. The SSH(N)s are notionally intended to cost a comparable amount to submarine classes of a major first tier navy, such as the Royal Navy. Instead of basing the UUVs to be carried on specific existing designs, which are likely to be obsolete by the time any SSH(N) might come to fruition (~possibly in 25 years hence[1]), it was considered to be more appropriate to assume believable generic UUVs.

[1] Considered by the candidate to be 25 years until for Concept Exploration commences across a number of first tier navies.

1.5 OUTLINE OF THESIS

The structure of the remaining chapters of the thesis is outlined Figure 4. The thesis falls into five parts. Firstly, Chapters 1 and 2 (blue boxes in Figure 4) review the existing evidence concerning the design of unorthodox submarine concepts, from which the research proposal is presented. It has been concluded that three research tools were required to meet the proposal: an operational analysis tool for UUVs (Chapter 3 in the green box); a tool to generate unorthodox submarine concept designs – including arrangements (Chapters 4 and 5 in the orange boxes); and finally, an approach to produce the refined solution space (Chapters 6 and 7 in the navy blue boxes). Finally, in Chapters 8 and 9 (yellow boxes), the thesis is discussed and concluded. The concluding chapter includes proposals for further work using the research approaches and tools developed.

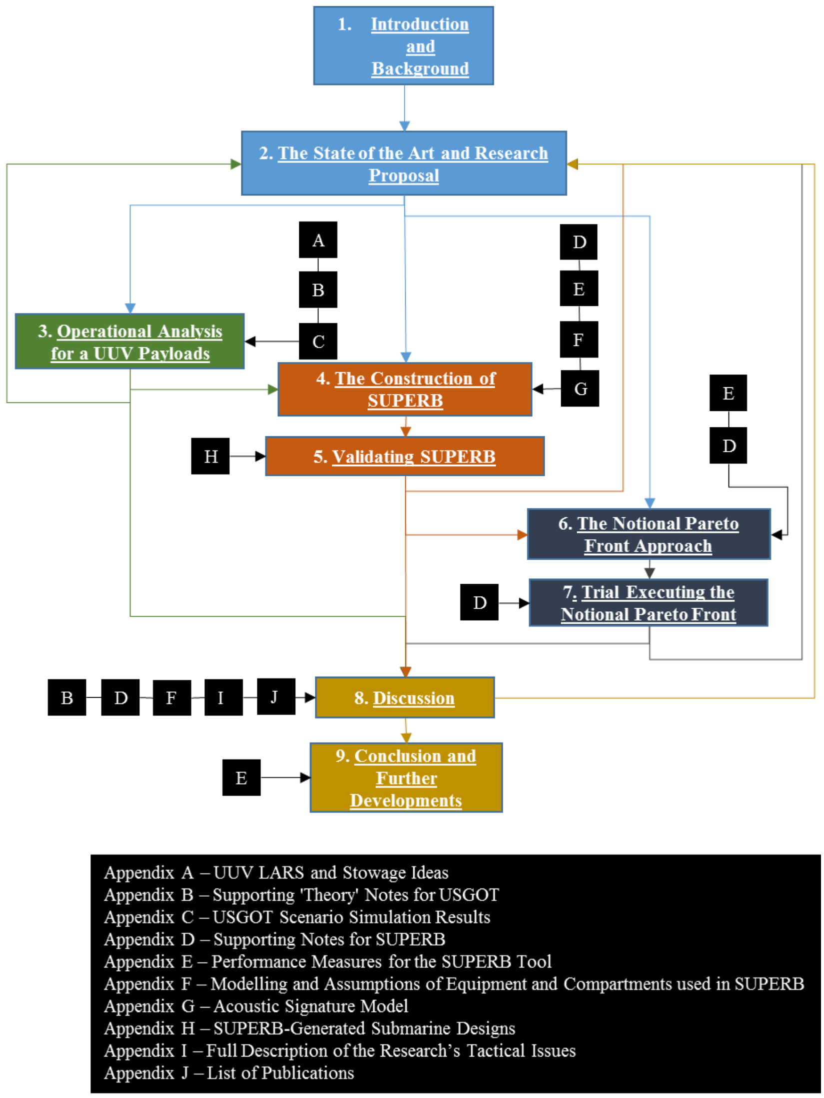

Figure 4 – Overview of the Structure of the Thesis

Chapter 2 consists of a review of the State of the Art highlighting the resources concerning the development of novel submarines, such as an SSH(N). From a ‘gap’ analysis, both the research proposal and the approaches and tools to meet the proposal are proposed.

Chapter 3 outlines an Operational Analysis (OA) tool to determine the capability of potential UUV payloads. It is called the UUV Grid Optimisation Tool (USGOT). The results of simulating three scenarios are used to provide a measure of effectiveness (MOE) for a UUV payload.

Chapter 4 outlines a (mostly) generic tool for generating submarine concept designs called the Submarine Preliminary Exploration of Requirements by Blocks (SUPERB). The outline includes the three sections of SUPERB: the mathematical modelling of physical features and equipment; the innovative arrangement approach (called Compartment X-Listing); and finally, the analysis of a concept design to determine if it is naval architecturally balanced (i.e. feasible).

Chapter 5 addresses the validation and verification of SUPERB, which is shown in three steps: Firstly, SUPERB is compared against a range of existing benchmark designs; then layouts produced by SUPERB under a set of constraints promoting ‘orthodox’ arrangement styles, are compared to the benchmark existing designs; finally, further validation of SUPERB and the Compartment X-Listing arrangement approach is achieved by reproducing a range of unconventional arrangements and designs.

Chapter 6 proposes an approach called the Notional Pareto Front (NPF) approach as a method for production the refined solution space. The chapter contains a mathematical description of the models used to calculate the cost and the ‘performance’ using a metric called the Metric of Tradeable Performance Characteristics (MoTPC). A sensitivity study has also been applied to the MoTPC. A description of how the NPF approach is intended to facilitate ‘conventional’ concept exploration studies ends the chapter.

Chapter 7 discusses the findings and viability of the NPF approach through a trial production, using SUPERB of the refined solution space for SSH(N)s.

Chapter 8 is split into three sections. The first section is a high-level discussion of the extent that the research has met the objectives laid out in Chapter 2 and, crucially, the research proposal. The second section concerns the ‘tactical’ issues that have arisen concerning the computer-based approaches and tools created to meet the research proposal. The last section concerns other issues, including the usability of the approaches and tools, miscellaneous issues and a discussion of the wider use of these approaches and tools.

Chapter 9 is divided into three sections: conclusions, possible improvements and further work. In the conclusion section, the key points concerning to what degree the work in this thesis has met the research proposal are summarised. The second and third sections of this chapter address both the technical side of improving the proposed approaches and tools and potential further work that falls outside the research's scope.

CHAPTER 2 - THE STATE OF THE ART AND RESEARCH PROPOSAL

2.1 INTRODUCTION

Having specified in Chapter 1 that novel problems, such as designing SSH(N)s, need the unrefined solution space to be investigated for concept exploration, the state of the art is reviewed in this chapter. The current ideas on SSH(N)s, have been examined in Section 2.2 to build a background understanding of the issues considered relevant to SSH(N)s. Section 2.3 considers how approaches exploring the solution space for ship design could use the output of the production of the refined solution space to undertake ‘conventional’ concept exploration. The approach adopted for ‘conventional’ concept exploration is considered in order to inform on the approach to be devised for the production of the refined solution space.

Given the potential unorthodoxy of SSH(N)s, the development of a ‘generic’ submarine design tool is considered necessary to explore a wide range of possible concept designs. This tool is based on the procedure for generic submarine design put forward by Burcher and Rydill (1994). To develop this tool, the state of the art in submarine concept design has been reviewed. To that end, Section 2.4 investigates design procedures that could be used to perform essentially generic submarine concept design and in Section 2.5, the approaches that could be used to perform internal submarine arrangement have been considered in a similar manner.

From this review of the state of the art, a research proposal has been formed, as well as the objectives to meet that proposal.

2.2 CURRENT PROPOSED SSH(N) CONCEPTS

An early example of a modular submarine concept was presented by Andrews et al. (1996). The paper demonstrated the architecturally driven ship design approach first proposed by Andrews (1981) applied to submarine design using the SUBCON tool for submarine concept design. The example submarine design presented by Andrews et al. had air-independent propulsion (AIP) and four large internal launch tubes located amidships and orientated athwartships. This design study was a preliminary investigation into the suitability of SUBCON for producing non-orthodox submarine designs. The submarine was a simple proof of concept exercise, and a concept exploration of the design space was not carried out. However, such an arrangement of mission modularity and launch tubes may not be readily extrapolatable to designs with much larger payloads of UUVs. Nevertheless, the study did produce a naval architecturally balanced design that showed a multi-mission modular submarine concept could be designed using that early version of the architecturally driven approach.

The demonstration of SUBCON by Andrews et al. (1996) was built on by Pawling and Andrews (2011) to produce a more comprehensive investigation on the SSH(N) idea. It contained a fully balanced SSH(N) concept design, as well as balanced UUV concepts. The approximately 5000-tonne "core Mothership design requirements" illustrated for a UCL DRC study (Table 3 and Figure 11 in Pawling and Andrews (2011)) specified a (Pressurised Water Reactor) PWR nuclear reactor for its primary propulsion with redundancy propulsion power from diesel generators. It was seen that if submarine designs of this displacement or greater are to be considered in a concept exploration, they should in all likelihood be nuclear powered. If smaller designs are to be considered then, it is conceivable that non-nuclear submarine designs would also be worthy of consideration.

Williams and Whitten (2011) presented a 12,000-tonne twin pressure hull concept study, which incorporated a bow payload module external to the pressure hull. This concept required a large external (free flood) volume to accommodate its UUVs stowed externally to the pressure hulls. This paper, unlike Pawling and Andrews (2011), had no supporting design analysis of the feasibility of such a design and it can thus only be considered a sketch study. However, it does suggest that unorthodox pressure hull configurations and larger displacements might be worth exploring in any SSH(N) design investigation.

The "core Mothership design requirements" in Pawling & Andrews (2011) specified externally stored torpedoes – suggesting that an unorthodox payload configuration should be considered in the concept exploration for an SSH(N) design. It is conceivable that for such a design, torpedoes would not be the primary weapon but just carried for self-defence. This could then reduce the required numbers of torpedoes to a level that could enable external storage of torpedoes. This, in turn, could provide space for internally stored UUVs. Pawling and Andrews concluded that an exploration of SSH(N) concepts should incorporate different configurations and payload sizes, both for the traditional weapons, such as torpedoes, and the novel payload of UUVs.

Binns et al. (2011) stated that looking further into the future; greater levels of autonomous operation are likely to be incorporated into the host boat and could result in requiring considerable external storage. Thus, UUVs could be operated, stowed and maintained external to the pressure hull. This was considered likely to result in decreasing the SSH(N)'s submerged (if not form) displacement due a greater amount of equipment being moved outside the pressure hull. The corollary from Binns et al. is that a comprehensive SSH(N) design investigation should consider both internal and external stowage of UUVs.

Williams and Whitten (2011) outlined the advantages and challenges of designing a modular mission submarine to a greater degree than Binns et al. (2011). Williams and Whitten considered the main advantage of such a modular submarine to be the ability to customise the submarine payload for specific roles. This suggested tailoring a UUV fleet for specific missions, which Operational Analysis (OA) could address. Additionally, Williams and Whitten acknowledged that the ability to perform maintenance on a UUV complement when externally deployed (but adjacent) to the host vessel would be advantageous for sustaining a mission, as time would not be spent capturing and relaunching UUVs. This suggested that consideration of extra space and equipment location should be addressed in concept design studies when investigating SSH(N) concepts. Williams and Whitten (2011) also pointed out that the flexibility of an SSH(N), compared to current SSNs, should result in fewer submarines being required to carry out the various missions of a submarine force. This is turn would imply that larger SSH(N)s might be more attractive by replacing the need for several different specialised vessels. However, Williams and Whitten also acknowledged that such vessels could be less efficient at performing each mission type as equipment and personnel carried for alternative missions would be redundant in specific missions. Thus, the consideration of large displacement submarines in an SSH(N) design investigation could be within the context of overall fleet performance. The mission modularity in Williams and Whitten's concept implies a level of 'future proofing' could be a property of such a submarine concept since the payload should be more readily modernised than non-modularised SSNs.

The few studies reported for SSH(N) concepts suggests that a wide variety of concepts, especially concerning payload configurations ought to be considered. Thus, there needs to be a clear method and toolset produced to explore potential SSH(N) concept designs. This proposed approach was considered to be 'generic', as it was seen as being required to generate a wide range of balanced concepts for exploring radical SSH(N)s options, within the limits of practicality and available information.

Producing a wide variety (and thus large number) of submarine concept designs, including arrangement, implies a coherent method from which a computer-based toolset could be devised to ensure that many potential solutions could be generated within a practical period (considered to be a few of weeks). However, it is acknowledged that generating architecture will not readily identify all design issues, such as operational practicalities. These design issues could be investigated by additional studies alongside assessment of the architectural design of a submarine.

Despite producing concept level designs ‘automatically’, the tool should still be directed by the designer and be capable of being examined (i.e. not be a ‘black box’ system) to verify the processes that the toolset adopts are valid in any particular concept investigation.

2.3 SET-BASED VERSUS DISCRETE DESIGN METHODS FOR CONCEPT EXPLORATION

2.3.1 INTRODUCTION

This section considers the process appropriate to the ‘conventional’ concept exploration of the refined solution space discussed in Subsection 1.3.1. It is considered that the type of approach adopted for ‘conventional’ concept exploration would be influenced by the approach devised to produce the refined solution space. This is because the output of the production of the refined solution space will drive ‘conventional’ concept exploration. Hence, the approaches to undertaking ‘conventional’ concept exploration are considered at this here.

Hagen and Grinstead (2010) have argued that consideration of other factors, such as new technologies, leads to an increase in complexity in a design at the early stages of design. Gaspar et al. (2012) also noted that the amount of information required to define a design should increase. Gasper et al. have provided a short summary of the ship as a complex system, which could equally be applied to submarines as a particular special case of a complex naval vessel. They described the Design Building Block (DBB) approach[1] by Andrews (2003b) (i.e. discrete designs explored in the Concept Phase of the design process (Andrews, 1994)) and the set-based design (SBD) approach proposed by Singer et al. (2009) as approaches to handling the high levels of information (and thus complexity) at the concept exploration stage of design[2]. In effect, these approaches could be adopted for

[1] DBBs were introduced by Andrews and Dicks (1997). DBBs can have both geometric and operational characteristics assigned to them and be assemble to form geometric arrangements, and are thus used in architecturally driven designs. Their use in submarine arrangement is covered in Section 2.5.

[2] Other approaches might be in existence but were not discovered.

'conventional' concept exploration. The discrete and set-based approaches are briefly described next before being compared to identify which is appropriate for 'conventional' concept exploration.

2.3.2 DISCRETE DESIGN FOR CONCEPT EXPLORATION

The DBB approach proposed by Andrews (2003b) fosters an exploratory approach for initial designs at the concept exploration stage without the need for fully resolved concept level designs, such as studies in Andrews and Pawling (2009). Andrews (2003b) approach involves the creation of a set of discrete and <u>architecturally driven</u> designs for the Concept Phase. The DBB approach has been adopted in preliminary ship design for both arrangement development as well as being key to whole ship synthesis. Other possible approaches, such as using genetic algorithms[1], require the specification of multiple discrete designs for concept exploration, as does the DBB approach.

Another possible approach to exploring the refined solution space using genetic algorithms has been presented by van Oers et al. (2008). This demonstrates exploring ship design using his Packing Approach to generate a large number (in the order of hundreds) of discrete designs with architectural descriptions. A Pareto Front of discrete designs was created, and subsequently analysed to produce a design, which could be used subsequently. Concept studies and their subsequent analysis can provide the designer with important design information even at the concept exploration stage of the design process (as outlined by Andrews (1994)). This facilitates the wide concept exploration without too much detail being necessary while a fuller design definition is required by the end of the Concept Phase. This avoids over-constraining the designer who might otherwise make premature material decisions, restricting those design trade-offs that are worth pursuing. A concept design with a lower resolution of detail could in effect be considered a bounded set of possible designs, which could be specified at higher resolutions following a set of yet to be taken design decisions. This sequence of decisions is demonstrated by Pawling & Andrews (2008) with the progression of modelling phases using the DBB approach for a ship design.

The prior guidance discussed in Subsection 1.3.1, which would come from adopting an orthodox style of design, may well not produce attractive solutions to *highly uncertain* problems. This would imply that if the design problem is *highly uncertain* (as complex design problems are likely to be), then a large number of discrete

[1] Genetic Algorithms are explained in detail later in Subsection 2.5.3

concept designs ought to be generated to enable a ‘conventional’ concept exploration to determine the preferred refined solution space satisfactorily. This was considered to be potentially very computationally demanding, as each discrete design ought to include an architectural layout.

2.3.3 SET-BASED DESIGN

Set-based design (SBD), as described by Singer et al. (2009), is based on delaying design decisions until sufficient information on the design trade-offs can be established. Multiple competing concepts progress concurrently through the design process, with elimination once they are considered inferior to other competing concepts by the designer[1]. Sets of system options are provided by sub-system experts (e.g. propulsion and sonar) and the ‘overlap’ (i.e. the bounds of an achievable whole design with all the systems synthesised) of these sets of system options is then considered from a whole-ship level performance stance. It is the ‘overlap’ of different system sets, which produce the group of competing concept designs. Frye (2010) has performed a demonstration of an orthodox style small concept-level design of an SSK of 1,000 tonnes, with critical interfaces prematurely defined in the design process, allowing subsystem development to start before fully understanding trade-off implications. This demonstration indicates that ‘conventional’ concept exploration using SBD is possible; however, Frye’s demonstration only concerns a ‘static’[2] design, which represents a very limited region of the solution space.

As design trade-off information is obtained (and more detailed requirements consequently elucidated), the set of valid system options will be further reduced to promote concept designs considered superior (by the designer using a user-defined objective function). This is achieved by the convergence of “overlapping” sets (Bernstein, 1998). “Overlapping” sets are combinations of system options, which when synthesised produce a ship that meets a set of criteria, such as achieving naval architectural balance and specified design characteristic constraints. Frye (2010) has suggested the advantage of SBD is that sets of system options are maintained further into the design process (to the end of concept) and hence system definition is delayed. This is intended

[1] The decision of determining preferred concept solutions in SBD is up to the designer, who uses any metric they wish. For example, in a demonstration of SBD for ships by Singer at al (2009) an objective function was assessed using a nonlinear optimisation (computer) program.

[2] A static design has been defined by Pugh (1985).

to increase the likelihood of a design solution being identified as both preferred and feasible by the designer and stakeholders.

Increasing the level of system detail through the design process reduces the set overlap and thus the variation in acceptable solutions[1]. SBD thus differs from the discrete approach as it considers simultaneously more than a single design, but within very narrow whole ship/system solution space, (for example the Ship to Shore Connector (SSC) outlined by Singer et al. (2009)). This restriction on the solution space suggests that SBD cannot readily handle novelty in a design problem, and instead can only consider evolutionary design problems, where the set of system options has been restricted before exploring a design. This infers that SBD can only consider an orthodox style of design, which would not be acceptable for the concept exploration of novel concepts, such as SSH(N)s. This is because, unlike most submarine designs (such as Nordin's (2014) Swedish SSKs), SSH(N)s are not evolutionary and there is the need to explore the unorthodox (e.g. multi-pressure hull submarines).

2.3.4 INDENTFYING AN APPROACH FOR THE CONCEPT EXPLORATION OF NOVEL SUBMARINES

The discrete approach using DBBs allows the alteration of the systems in a single concept design to occur further into the decision process as any alterations can be applied to individual designs, which then means the design implications of the alterations could be appreciated holistically. In contrast, SBD requires the sets of systems to be pre-set by the human designer. However, according to Frye (2010), this ability to alter systems is lost once concepts progress to a fidelity level that is sufficiently high to specify subsystems i.e. once the Feasibility Phase has begun. It was appreciated that both these methods require metrics to be employed to determine preferred concepts designs in a cost and performance trade-off process. This then makes the creation of these metrics an objective in designing a generic submarine design tool.

Bernstein (1998) described the SBD approach as first requiring the solution space to be defined and then a search conducted by removing those spaces which promote inferior designs (i.e. reducing sets), once they have been identified. He also advised that solutions should only come from within sets, i.e. the set should not be enlarged. This would imply that during the initial set up of the concept exploration, the set bounds for all sets

[1] The number of competing concept designs can be increased again by increasing 'manually' the population of system options known to inhabit the converged overlap space.

must be initially defined. This was evidenced by the experience of the programme for the US Navy's Ship to Shore Connector (SSC) replacement for the Landing Craft Air Cushion (LCAC), which was designed using SBD (Mebane, et al., 2012). This is the only design to date developed by the US Navy using SBD and was a design evolution based on an existing design (as evidenced by Mebane et al. as having similar operational requirements and solution style to the existing LCAC it was to replace). Before implementing the SBD process, Mebane et al. reported that the design team's organisational structure was first defined by major system areas. Such initial definition could hinder the consideration of novel technology, as no such expert knowledge (due to the unfamiliarity of the technology) would be available to promote system options that might have proved superior to the pre-selected LCAC-derived option. Frye (2010) remarked that the set options in SBD should be driven by operational requirements. If the operational requirements are not fully defined, as be the case if a Requirement Elucidation approach is properly adopted in the Concept Phase (Andrews, 2003a), and cannot be subsequently identified and defined through the concept exploration stage as suggested by Frye, it follows that options for alternative sets may not be readily defined. It was considered for novel concepts that this would likely increase the probability of unattractive concept solutions being generated as the assignment of set overlaps might be questionable, due to the interactions of novel technologies with other systems not being fully understood due to the insufficient fidelity of the design solution.

One way of decreasing uncertainty in the definition of sets when a new technology is used would be to use larger (i.e. more inclusive) sets, to cover more system options. However, it was considered this could raise the required amount of computation to impractical levels, as a larger set of concept designs would have to be analysed. This was indicated by Frye (2010), who used a SBD approach to generate a conceptual diesel-electric SSK of about 1,000 tonnes displacement. Frye reduced the combinations of options for systems by assuming some influencing design factors (such as hull configuration for the hull system) did not have a sufficient impact on the concept's design. However, this implies prior knowledge of the significance of a design factor on the overall submarine design – something that may not always be readily available when considering concept designs that incorporate novel technology. Frye was able to go on to use SBD to generate 44 concept designs with physical equipment defined by using equations given in Burcher & Rydill (1994). However, the equipment was not arranged, so Frye's design solutions had only the very broadest measure of naval architectural balance. Nonetheless, this suggested that if prior knowledge of setting up of (likely restricted) sets for novel concepts was able to be obtained *a priori*, SBD could subsequently be used to investigate novel concept designs within a limited region of the refined solution space. However, for concept exploration to be properly undertaken in the refined solution space, it was considered that internal compartment arrangement should be undertaken, so that the architecture could be audited and a design be shown to be balanced beyond the crude level of design acceptability used by Frye (2010).

It was concluded that while SBD could be potentially applied to undertake 'conventional' concept exploration of the refined solution space, it would be poorly suited to considering significantly novel designs (such as the SSH(N) concept). Sufficient knowledge of the design implications of a novel technology (including architectural knowledge) would likely have to be first obtained if all the possible sets of system options were to be confidently obtained. SBD, by its very nature of considering simultaneously multiple possible designs, does not readily allow, due to impractically high numbers of discrete designs, the generation of an arrangements for assessment during the Concept Phase.

In order for concept exploration of a novel vessel in the unrefined solution space to be confidently performed as a large number of discrete designs would be required. This would probably make using Andrews (2003b) approach using DBBs (and other 'manual' discrete design approaches) unsuitable due to impractically high levels of design effort for a large number of detailed designs. However, if the refined solution space could be first defined, 'conventional' concept exploration using discrete designs could then be potentially acceptable.

Evidence that the definition of the refined solution space could lead to the identification of submarine concept designs suitable for advancement is implied by Biddell (1998). Biddell (2000) attempted to validate his Submarine Concept Aid (SCA) design tool (which produces discrete conceptual investigations) by comparing solutions produced from a group of submarine operational concepts to meet a set of requirements that were independently suggested by a set of experts. Biddell (2000) explored of a region of the refined solution space, using a group of locally focused concepts produced by SCA, based on what he called "*a known good design*". It should be noted that SCA uses a very broad definition of acceptability and not a full definition of naval architectural balance at concept level. Hence, the output of SCA cannot be considered concept designs, even to a conceptual level. The region of the unrefined solution space was effectively bounded by the generic algorithm's rules and selection of a 'good' starting solution design[1] on which the genetic search algorithm then generated a group of conceptual 'designs'. The generic algorithm generated 'designs' that seemed to be close to a known 'good' point (making them likely to be evaluated as 'good' as well). The genetic algorithm's rules meant that any 'design' that did not meet the specified performances or were unbalanced would not have been allowed to propagate, as these would have hindered the exploration of submarine concept designs. By basing the latter group on a pre-selected 'good' 'design', the group of 'designs' in the (localised) refined solution space would have been a set with a high proportion of 'poor' and/or infeasible (i.e. unbalanced) designs having already been effectively disregarded. This indicates that if 'conventional' concept exploration could be directed into regions of the refined solution space based on 'good' 'designs', superior (as defined by some user-defined metric) discrete designs could be obtained in the refined solution space to advance further in the Concept Phase of the design process.

2.3.5 CONCLUSION

This section has discussed the applicability of the discrete architectural approach (Andrews, 2003b) and the set-based approach put forward by Singer et al. (2009) for the concept exploration of a novel vessel. It has been concluded that both approaches could be used to explore the refined solution space for novel designs, however, it was concluded that SBD is only likely to deliver if it can be focussed in a very limited region of the solution space. The work of Frye (2010) has demonstrated that SBD could be applied to submarines for a 'static' SSK design, however, it was considered that the design implications of any novel system would first have to be investigated and a compartment arrangement additionally generated to ensure realistic naval architectural balance. It has thus been concluded that 'conventional' concept exploration for novel concept designs would require solutions with a synthesis including an architectural definition. Thus, any approach devised for production of the refined solution space should be discrete based and architecturally driven. It was also concluded that some metric to determine preferred concepts designs need to be devised, if concepts designs in the unrefined solution space are to produce acceptable subsequent designs. The development of an

[1] The design was based on the RN's *Trafalgar*-class SSN. Thus, it is considered by the candidate that this design should be naval architecturally balanced, but Biddell does not appear to state if this is the case.

architectural-based submarine design tool that can populate the unrefined solution space and subsequently allowing production of the refined solution space is considered in the next two sections of this chapter.

2.4 ‘GENERIC’ SUBMARINE DESIGN TOOLS

2.4.1 INTRODUCTION

For any novel and, potentially, radically different submarine design, such as the proposed concept of an SSH(N), the adoption of the traditional evolutionary approach to design, based on the extrapolation of current submarine designs, is considered questionable. The incorporation of the stowage and the Launch and Recovery Systems (LARS) for substantial UUV payloads would introduce novel physical features, which are not necessarily compatible with the style of design of ‘orthodox’ evolutionary-based submarines. This style of design has been dominant in the Western World for approximately the last 60 years (Binns, et al., 2011), i.e. the nuclear-powered submarine era. An ‘unorthodox’ design in the current research is one potentially adopting novel physical features or a set of arrangement relationships which could yield a design that significantly differs from the orthodox (i.e. currently prevailing) design practice. This could either be the incorporation of a new major equipment (affects the weight distribution at the one-digit breakdown level[1]), novel major physical features (e.g. twin pressure hulls) or an unusual arrangement style (e.g. a forward-located nuclear reactor). Thus, any concept incorporating a significantly large UUV payload could be considered to be an ‘unorthodox’ design and ought to be designed by applying a ‘first principles’ approach. The generic design procedures reviewed in this section can be related to the “Three Stages Model” by Dym and Levitt (1991), which is an iterative process of generation, arrangement and assessment. Other procedures can considered to be more complex versions of this model.

Thus, this section of the state of the art review begins by considering the current literature available on designing generic submarines from ‘first principles’. Van der Nat (1999) stated that a new submarine design has traditionally been explored and analysed in two ways: either the preference for new submarine designs, which are closely related, (i.e. ‘evolved’) from an existing design or, alternatively, a time consuming and resource intensive investigation of proposed new designs. These represent two extremes on a continuum of resources

[1] The weight on a submarine can be divided into typically nine groups defined by their function. This is called a one-digit breakdown. These nine groups can be further subdivided (two-digit breakdown) and sub-subdivided (three-digit breakdown) by function or ‘trade’.

expended and knowledge captured from reviewing new designs. Van der Nat remarked that this situation does not encourage the exploration of new (and different) designs and proposed that a tool be created to provide "fast and flexible" analysis, to break away from traditional approaches. Van der Nat defined a 'flexible' tool as one in which "new knowledge can be integrated easily, that a wide variety of design problems can be answered and that the design of the boat remains adjustable." The rest of this chapter discusses the creation of an approach and associated design tool to fill the 'gap' between van der Nat's two extremes.

The first subsection (Subsection 2.4.2) explores generic design procedures to place in context designing submarine concepts from 'first principles'. Next, Subsection 2.4.3 considers the mathematical relationships, which could be used to model mathematically a submarine design, such as an SSH(N). This is followed by a review in Subsection 2.4.4 of the data sources that could be used to populate the mathematical models used to design an SSH(N).

2.4.2 GENERIC DESIGN PROCEDURES

It is important to review procedures, which are considered capable of generating potential submarine concept designs that have differing "styles". "Style" was introduced into ship design by Brown & Andrews (1980), and Andrews (2012) and Pawling et al. (2013) have provided a definition. "Style" in ship design is a set of aspects that influence the whole system rather than just discrete systems. Andrews (2012) specified examples in six categories for these aspects, many of which are not readily quantifiable.

Preferred style choices for SSH(N)s can emerge from producing the refined solution space, and can thus be used as inputs when undertaking 'conventional' concept exploration. This is in contrast to other submarine concept procedures, such as the one used by Nordin (2014), in which a given style of design was pre-specified, to promote the selection of more attractive concept designs based on performance using Operational Analysis (OA). Nordin was thus able to generate a concept design by using specific requirements (e.g. stealth and operational envelope) to translate directly into a systems definition in his "Play-Cards" synthesis method, and then straight to a general arrangement. Nordin's approach was intended to explore a focused region of the solution space for a limited set of scenarios. It is therefore considered inappropriate to adopt Nordin's approach as the generic design procedure to widely explore the solution space for novel concepts, such as SSH(N).

In Chapter 11 of Burcher and Rydill (1994) a generic design procedure is outlined (which is broadly similar to Dym and Levitt's model) and was considered appropriate as a basis for generating SSH(N) concept designs, due to a track-record of being used to produce a wide variety of submarine designs on UCL's postgraduate submarine design course (NAME Office, University College London, 2014). Burcher and Rydill's procedure is shown in Figure 5.

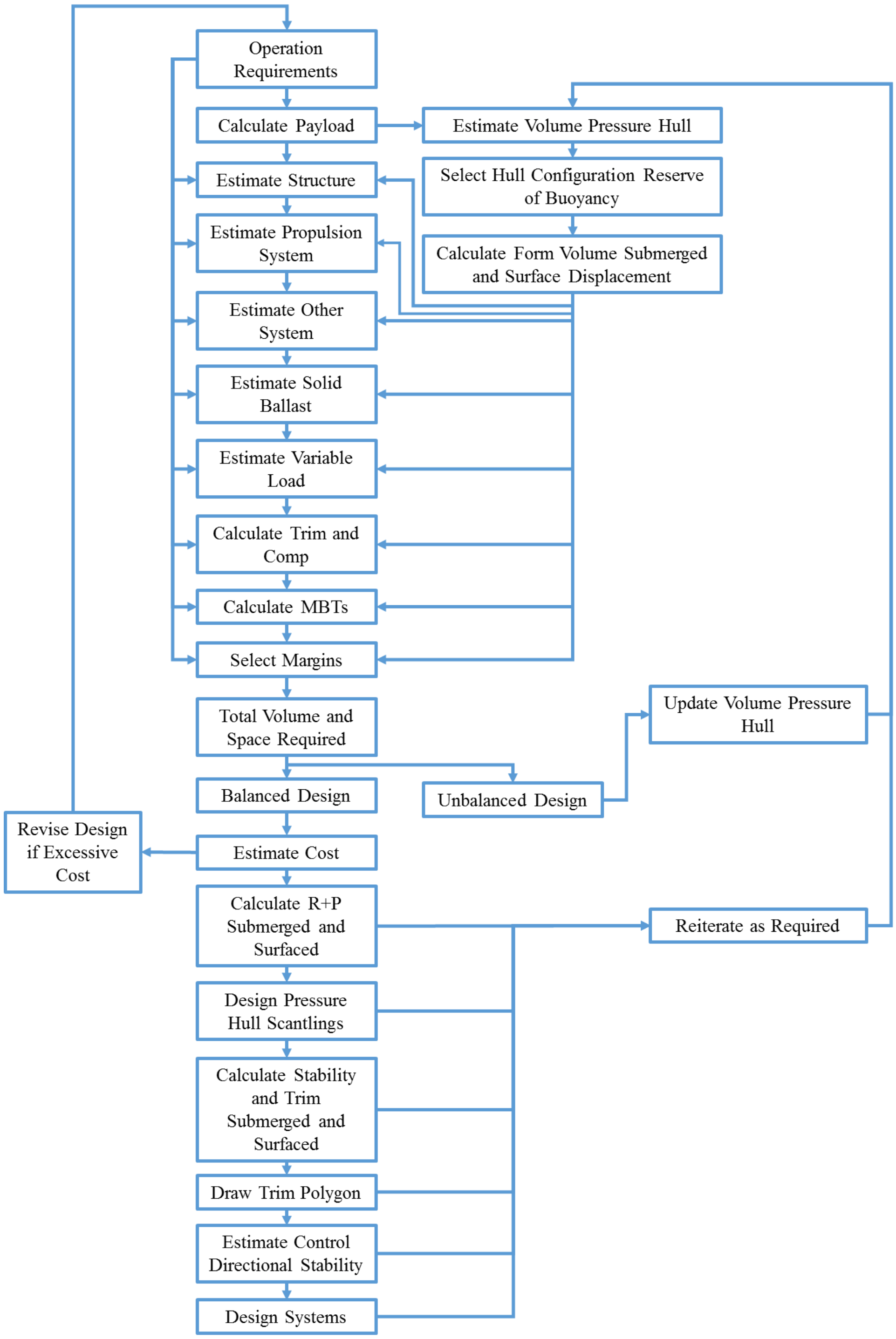

Figure 5 – "Submarine Sizing Procedure", Figure 11.4, pp 265-7 of Burcher & Rydill (1994)

The advantage of using a generic design approach is that it is not bounded entirely by current design practice, thus making it highly relevant to designing unorthodox submarine concepts. On this basis, a hosted UUV fleet and resultant Launch and Recovery System (LARS) and stowage equipment is considered to be “Payload”, which would be consistent with Burcher and Rydill’s (1994) the definition of payload. This is because the UUV fleet was seen to fulfil similar functions to a traditional payload, in that, both are capable of delivering the submarine’s Intelligence, Surveillance and Reconnaissance (ISR) requirements and potentially, its ASW/ASuW capabilities. Another procedure for generic submarine design that is similar to that of Burcher and Rydill (1994) has been qualitatively described by Gabler (1986). The procedure in Gabler could be considered sufficiently consistent with Burcher and Rydill’s procedure (1994) to provide insight into the rationale behind their procedure.

Andrews et al. (1997) in the IMDC ’97 report on the state of the art of marine design methodology outlined a generic design sizing procedure (within an overall ship design process) that is similar to the one suggested by Burcher and Rydill. Andrews also gave accompanying assumptions and possible sources of data for each step in his procedure (appropriate in his case to a typical naval surface combatant), which were considered useful when adopting Burcher and Rydill’s generic submarine design procedure, since both of Andrews’ set of examples provided insights into how a generic submarine design procedure developed for SSH(N) concept exploration could be created.

Kormilitsin and Khalizev (2001) outlined some alternative approaches to Burcher and Rydill’s (1994) procedure for early stage submarine design. These approaches were used to design Soviet submarines in the 1960s before the advent of modern computing, and thus, they are considered by the candidate to be outdated. These approaches are the drawing method; the graphoanalytical method; and the analytical method. These methods represent different points on a spectrum of possible early stage design procedures, ranging from using a specific set of analytic formulae to just using drawings of submarine geometries. It was however considered that these alternative methods for generic submarine concept design would not provide the same level of precision in producing a naval architecturally balanced design as would the method proposed by Burcher and Rydill (1994), and were thus rejected.

Biddell created his SCA tool to generate submarine ‘designs’ as an alternative to the generic procedure suggested by Burcher and Rydill (1994). SCA uses expert systems knowledge to predefine equipment options with preferred performances at the system level, in order to achieve the SCA-defined decomposed functions of a submarine. SCA then uses transverse sections of a typical submarine design to divide a design into a series of longitudinal sections, with equipment options assigned to sections. Each section has its own profile of whole-boat properties, such as electrical demand and required volume. The arrangement is generated, and longitudinal balance is achieved, by first scaling and then using a genetic search algorithm to order the sections longitudinally while obeying a set of arrangement constraints. It also does not produce designs that have been completely assessed for naval architectural balance (at a concept level). SCA does not consider variations in the trim conditions of the submarine, which comes from considering the internal arrangement at the whole-boat level.

While SCA has the advantage of considering all required systems simultaneously, it comes at the cost of having to rely on using a typical and thus orthodox style of design to define transverse sections. As the preferred style of design for SSH(N)s has yet to emerge, there is no available style of design which SCA could use as a basis for its transverse sections. It was concluded that this makes SCA unsuitable for generic submarine design. Furthermore, potentially novel (i.e. unorthodox) submarine designs could have sections that are difficult to arrange reliably. Any incorporation of a novel technology clearly means that there is a lack of sufficient knowledge from which to provide sufficiently plausible options for a specified performance. The location of the UUV storage and LARS could be one such instance and so would decrease the confidence in any SSH(N) design produced by SCA, if it was adopted for generic submarine design.

The functional decomposition in SCA could be limiting for designing novel submarine concepts, since defining individual functions is likely to be uncertain. For example, the launching of small UUVs and torpedoes through torpedo tubes could be considered a single function or two separate but related functions. This, in turn, promotes a higher level of uncertainty that the solution provided by SCA is the ‘optimum’ one (according to SCA’s objective function), due to the possibility of overlapping system boundaries. It was considered that the procedure presented in SCA would be unsuitable for ‘generic’ submarine design and that only defining systems sequentially would be appropriate.

Van der Nat (1999) discussed an approach to generic submarine design through the creation of a submarine concept exploration tool called SUBCEM. Van der Nat observed that ‘traditional’ submarine concept exploration tools still used a “directed network of design relationships” to quickly generate a set of similar concepts. The directed network is a pre-set procedure for generating objects, which are then arranged to a pre-set general arrangement template. Design parameters (such as speed and depth) can be altered to generate alternatives within a narrow range[1] to ensure that the pre-set arrangement template is still conducive to producing naval architecturally balanced submarines. Van der Nat also observed that the direct network only considers the properties of the objects and not their arrangement, the latter of which van der Nat considered crucial to exploring new submarines with different sets of design requirements. With the novelty expected for SSH(N) concepts, it was considered that differing arrangements must be considered and so using pre-set arrangement templates was seen to be inappropriate.

Van der Nat (1999) proposed a solution to the limitations imposed by the directed network approach, which he called the “undirected network approach”. He considered this solution should be able to produce designs that have arrangements that do not fit rigidly into a pre-set arrangement template (although the SUBCEM tool still adopted an ‘orthodox’ arrangement style derived from expert knowledge[2]). In this approach, the design problem is divided into a series of sub-problems (e.g. the sizing of equipment in the propulsion system to achieve given speeds) that are converted into a definition of physical features and systems. Van der Nat proposed that the overall problem could be solved by first solving each of these subproblems, while also considering the undirected connections (i.e. relationships) between sub-problems. Van der Nat also acknowledged that various sources of relevant knowledge would be required for the proposed approach. In calling SUBCEM ‘flexible’, van der Nat (1999) stated that new knowledge could easily be integrated. It was thus concluded that for any generic design tool created for the generation of SSH(N) concepts, new knowledge would need to be obtained for the novel UUV payload. This knowledge should include possible physical and operational properties of the UUV payload and an indication of the intended performance and range of UUV craft to be deployed.

From this consideration of the limited set of procedures existing for generic submarine design, any new proposal should be based on Burcher and Rydill’s (1994) approach, as it is the only viable procedure to design novel submarine concepts from ‘first principles’ and thus able to deal with the levels of novelty anticipated.

[1] The acceptable range of a design parameter was defined by the variance in parameter value that still resulted in naval architecturally balanced designs being produced while using the pre-set arrangement template. This limitation implies that this approach may only explore a narrow region of the possible solution space.

[2] SUBCEM arranges a set of related of objects to a cell (of which multiple cells make up the internal space of a submarine). The objects are not specifically located in a cell, rather their consumption of a cell’s geometric quantities (e.g. volume and length) are assessed as they are sequentially allocated. The allocation order of objects to a cell is mathematically optimised to produce superior packing. From this order and the geometrical properties of the objects, the object locations can be inferred.

2.4.3 MATHEMATICAL RELATIONSHIPS FOR SUBMARINE DESIGN

The mathematical modelling of compartments and equipment was also considered as a part of the procedure to translate top-level characteristics (such as diving depth and maximum speed) into physical features and equipment. It was concluded that the physical features and equipment could then be subsequently arranged to produce concept designs by some arrangement approach (which is explored in Section 2.5).

The relevant mathematical relationships are driven by both physical laws and established good practice[1]. These imply that some style decisions are made in the adoption of a specific set of mathematical relationships. For example, the adoption of a certain mathematical model implies certain design characteristics of a pressure hull. Different styles could be adopted using the ‘generic’ submarine design tool by allowing the designer to choose from a range of options. The range of options would be defined by a set of top-level characteristics that were initially selected. For example, the tool could have mathematical models able to represent single and twin pressure hulls, and the designer could toggle between these options and affect the chosen architectural style of the submarine study, thereby making a stylistic decision.

Burcher and Rydill (1994) comprehensively covered the basics for many elements of submarine design and thus provided a very sensible starting point to design new submarine concepts from ‘scratch’. In particular, Chapter 11 of Burcher and Rydill entitled “Generating a Concept Design” gives several simple mathematical relationships to produce certain top-level characteristics, such as manning levels and Reserve of Buoyancy (RoB). Such mathematical relationships are also detailed in the Design Procedure of UCL’s postgraduate Submarine Design Course (NAME Office, University College London, 2012c). These were considered sufficient to provide mathematical models for the top-level description of a submarine concept design. Kormilitsin and Khalizev (2001) have also provided a further source of mathematical relationships for a range of aspects appropriate to early stage submarine design, however given the distinctly different style of design, these have been used with some caution.

Another source of mathematical relationships on many aspects of submarine design was provided by the US Navy designer Jackson (1983). While some of the data in Jackson’s paper is possibly out of date and unlikely

[1] “Good Practice” is considered to be a set of design decisions that are sensible and lead to a design being practical. For example, putting the stowage of torpedoes next to the torpedo tubes

to account for submarine developments in the last 30 plus years, most of the mathematical relationships were considered to be still sufficiently relevant for use at the concept level of design fidelity. This was not considered surprising as many of the relationships are driven by the invariant laws of physics. The availability of Jackson's (1983) paper, on which the US Navy/MIT submarine course is based, suggests that mathematically modelling relatively novel concepts (such as an SSH(N)) could be possible. However, proof of the suitability of mathematically modelling a submarine by Jackson's relationships would have provided more confidence in adapting his algorithms for novel design concepts.

It was considered that mathematical models were useful as a starting point for the generation of SSH(N) concepts. However, due to the low level of fidelity at the concept level given by these mathematical models, it was decided initial design decisions could be over-constrained by decisions made with unreliable or incomplete information (van der Nat, 1999). Thus, it was considered that simply using mathematical models to describe the equipment and physical features might not provide the designer with sufficient information to produce potentially unorthodox designs, to inform for proper concept exploration (Andrews, 1994). Furthermore, it was concluded that additional design exploration, including producing arrangements of sets of compartments, ought to produce adequate submarine definition. Then, such designs could be properly assessed for sufficient naval architectural balance appropriate to a concept level of design definition.

2.4.4 DATA AND INFORMATION FOR A MODELLING A SUBMARINE

The mathematical relationships mentioned in the previous subsection require data to generate the physical features necessary to model a prospective submarine. Similarly, other (non-numeric) relationships and rules need to draw on specific sources for appropriate knowledge. Andrews et al. (1996) saw the reason for the paucity of data for submarine concept designs, as chiefly due to the lack of classes built in comparison to surface ships. It was therefore concluded that a generic submarine concept tool was required to supplement the available published data using data from another source. UCL runs the postgraduate Submarine Design Course, which each year produces a set of novel submarine designs using an unclassified but believable database (NAME Office, University College London, 2012b)[1]. These designs have been 'worked up' to a naval

[1] UCL also runs a postgraduate sister course as part of a taught MSc in Naval Architecture for surface ship design. The data book for ship design (NAME Office, University College London, 2012a) also contains some information applicable to submarine design.

architecturally balanced level appropriate to the concept definition and thus were considered a suitable source of data.

Burcher and Rydill (1994) provided some typical weight and volume breakdowns at the one digit level for SSNs, with similar data from Kormilitsin and Khalizev (2001). These sources were considered that these two sources of data could complement each other as they focus on submarines produced by differing design doctrines from the Cold War (see Polmar and Noot (1991)). This was considered to provide a sufficient range of data from which SSH(N) concept designs could be generated, rather than relying on a single source of data and gave a better level of confidence that the data used would be realistic. A further source of data is that from Arentzen and Mandel (1960), however, the paper is 55 years old, and so some of their data could be obsolete and therefore more recent publications were considered more appropriate. Nevertheless, that comprehensive survey provides relevant background, especially with respect to some fundamental submarine issues which have been largely unaffected by subsequent technological progression.

While these sources of data were not considered definitive, they did provide guidance in producing SSH(N) design proposals. An SSH(N) has to obey the relevant laws of physics, meet the same design constraints and utilise many aspects of orthodox submarine design, such as ballast placement for hydrostatic balance and workable accommodation arrangements. Hence, it was considered likely that a naval architecturally balanced SSH(N) concept design would exhibit a similar weight and volume breakdown profile to existing submarines once the special peculiarities of an SSH(N) have been taken into account. More qualitatively, the paper by Daniel (1983) provided a high-level discussion of the various aspects of submarine design, with descriptions of some of the technical challenges. Such information could be used in creating a tool for generic submarine arrangement since it described 'hard constraints' which must be obeyed when arranging the compartments of a submarine. Hard constraints are relationships between submarine components that cannot be violated if a feasible submarine concept design is to be produced. An example of such a hard constraint would be the attachment of the propulsor to the drive shaft. Since Daniel's paper is also over thirty years old, recent and near future technological developments, such as Independent Fully Electric Propulsion (IFEP) (Hodge & Mattick, 1997) were also considered when adopting apparent hard constraints.

2.5 GEOMETRIC ARRANGEMENT TOOLS

2.5.1 INTRODUCTION

The procedure provided by Burcher & Rydill[1] (1994), does not sufficiently specify the arrangement of physical features and equipment in a submarine. Thus, this section includes a review of the available arrangement tools (summarised in Table 3), which were considered to provide a basis for an approach to creating a wide range of novel submarine design concepts, such as SSH(N)s. The effect of incorporating a significant payload of UUVs into a submarine design, suggests more attractive SSH(N) designs could differ from those produced by aping current arrangements, and with the UUV features 'shoe-horned' in. This was considered likely to increase the chances that these potentially more attractive SSH(N) designs would then emerge during a design investigation. Attractiveness was defined by designs that were naval architecturally balanced to a concept level and possessed a superior performance[2]. Due to a paucity of arrangement methods specific to submarines, ship arrangement methods were also investigated. Thus, ship tools were assessed as to whether they could be adapted for submarine concept designs. This section discusses the two main types of geometric ship arrangement approaches: genetic algorithms and the Design Building Block (DBB) approach.

Table 3 - Summary of the Three Reviewed Arrangement Approaches[3] (Pawling, et al., 2013)

Tool	UCL (DBB)	Uni. Michigan (ISA)	T.U. Delft (Packing)
Driver	Volume	Area	Volume
Full Ship Design	Yes	Deck Arrangements Only	Yes
N Dimensions	3D	2.5D	2.5D or 3D
Computer-Generated Layouts	User Drag–and–Drop	Yes	Yes
Optimisation Scheme	Manual	HGA-MAS[4]	GA[5]
# Feasible Concepts	Few	Hundreds	Hundreds
Adaptable Hull Shape	Yes, can be wrapped	No, fixed from ASSET	Yes, between designs

[1] In Chapter 7.4 of Burcher & Rydill (1994) the Flounder Diagram is put forward as aid to internal arrangement. The Flounder diagram demarcates the cross-sectional area supply or demand to a base of longitudinal length of a pressure hull and internal compartments respectively. The diagram provides a useful assessment to of an internal arrangement's overall volume demand, but does not accurately take into account an arrangement's 'true' layout, which may not be distributed in a suitable manner for naval architecturally balance at a concept level.

[2] Performance was assessed by a metric called the Measure of Tradable Performance Characteristics (MoTPC). It is described later in Section 6.2.

[3] Table reproduced from Pawling et al. (2013).

[4] HGA – MAS = Hybrid Genetic Algorithm – Multi-Agent System

[5] GA = "Genetic Algorithm".

2.5.2 THE REASONS FOR COMPUTER BASED ARRANGEMENT TOOLS

The State of the Art report on Design Methodology for IMDC 2012 by Andrews et al. (2012) stated that there has been a paradigm shift in ship designs methods. This has been caused by using modern day computing that allows high levels of Computer-Aided Graphics and simulation techniques that enable arrangement design to be incorporated into Computer-Aided Ship Design and so has opened up previously impractical approaches.

Andrews et al. (1997) in the State of the Art report on design methodology for IMDC 1997 discussed the relationship between novelty (and hence risk) in new ship design and the accompanying validating research work. The implication for the current research is that for an SSH(N), which is considered likely to be a vessel with a high degree of novelty, due to the inclusion of several new technologies into its design, some level of solution space exploration would be necessary. This was therefore concluded that computer-based arrangement tools would need to be developed as part of the generic submarine design tool.

Traditional ship design was challenged by Andrews (1981) who proposed that designs should be based on an architectural approach to avoid the “downstream tyranny” that occurs in complex ship design. The downstream tyranny was said by Andrews (2003a) to be the premature limiting of exploring radical design options by subjective decisions, which focus on setting the functional definitions of a vessel without regard to material options informing requirements, cost and risk. The architectural approach has become practical due to advances in computer technology that allow for ever faster computation rates, and crucially, the ability to readily render and alter three-dimensional geometric images of complex entities, such as naval vessels. This, in turn, allows the designer to recognise design issues that might not otherwise be immediately apparent in a table of numbers or on a two-dimensional drawing but become significant once a three-dimensional arrangement drives design decision making. Additionally, the computer modelling of arrangements has facilitated at the concept design level of detail more realistic calculations for measures of ship performance, such as stability. This enables the capture of more knowledge and, potentially, of greater importance at the concept level of the design process, which Nordin (2014) considered to be a more efficient deployment resources in the design life cycle. Ideally, any submarine design tool, which investigated SSH(N) concept designs, would require similar knowledge capture at the concept level to that of presented by Nordin in his twenty-year research programme. The fully integrated Computer-Aided Design (CAD) approach, which describes architecture numerically and spatially, is thus potentially effective in revealing the key design decisions and problems when conceptualising novel designs – something considered essential when designing an SSH(N).

The rest of this section explores approaches used to generate arrangements using computer tools.

2.5.3 GENETIC ALGORITHM BASED APPROACH

A genetic algorithm allows dominant designs to evolve and produce superior 'children' by combining more optimal characteristics (as determined by some specific metric). Random mutation is also encoded into 'genes' (typically for arrangement, this would be the order in which compartments are located) to ensure consideration of a broad spectrum of possible alternatives. After successive generations, the genetic algorithm should converge on an 'optimum' design or set of designs. The evolution of successive generations can be guided by a set of constraints or objectives. Duchateau et al. (2015) explored three different approaches for guiding a genetic algorithm for ship design towards an 'optimum'. These were packing rules driven (described by van Oers (2011)), search algorithm constraints driven, and objective-driven search algorithm. Objective-driven steering was preferred by Duchateau et al. largely because of "*its ability to manage unforeseen conflicts between identified criteria*". Duchateau et al.'s objective-based 'optimum' utilised seven objectives (e.g. a minimum sprint speed and packing density), with preferred designs meeting more (but not necessarily all) of these objectives, than 'non-optimum' options. The University of Michigan (UoM) have developed a genetic algorithm-based method called Intelligent Ship Arrangement (ISA), (Daniels, et al., 2009). The ISA plugs into the US Navy's primary naval ship synthesis tool ASSET (Advanced Ship Synthesis Evaluation Tool) (Beyer, et al., 1990) and can generate successive generations of ship design, from which preferable designs are retained and fed into another iteration of ISA until a design solution is found. ISA has a two-step method for allocating spaces (containing objects to arrange) into a two-dimensional grid (called Zone-decks) defined by a ship's decks and main watertight bulkheads (WTB) with the subsequent arrangement of allocated spaces within each zone-deck. This two-step approach has been called a Hybrid Genetic Algorithm – Multi-Agent System (HGA-MAS) because it combines a genetic algorithm with an agent-based approach. Allocation of spaces to Zone-decks is affected by fuzzy constraints due to geometric (e.g. required area) and relational (e.g. adjacency) constraints, and their allocations are driven by the genetic algorithm. The localised arrangement is then conducted by "agents[1]" utilising fuzzy constraints to form the spaces into a topology, which are optimised by an objective function[2] operating at the local (individual space) level. The agents can alter a space's geometry to form a spatially efficient topology. The agents can also alter the allocation of spaces from one adjacent Zone-deck to another if these alterations improve the overall design of the ship. The overall arrangement is then fed back to the allocation phase so that the generic algorithm can direct allocation to generate new allocations. In a description of ISA provided by Parsons et al. (2008), ISA was seen only to subdivide a frigate-size general arrangement into Zone-decks. ISA was seen to lack the capability to alter the major structure of the ship, which was concluded to be a major drawback by the candidate of using ISA (or something with a similar objective function) for investigating the design a naval vessel with unknown preferred dimensions, such as an SSH(N).

The Design for Layout State of the Art Report to IMDC in 2012 by Andrews et al. (2012) commented that using a generic algorithm is well suited to optimising a multimodal 'flat' problem (i.e. few local minima and incremental improvements in successive iterations), such as for arrangement (starting from a given arrangement style). However, it was concluded by the candidate that arrangement optimisation during the conceptual exploration of novel submarines, such as for SSH(N)s, is not sensible. This is due to the difficulty in devising a robust yet adaptable whole-boat level objective function, which is applicable to the wide range of solutions that should be considered during concept exploration. The lack of knowledge on the arrangement characteristics for novel physical features, coupled with the low level of fidelity at the whole-boat concept level, strongly suggests that determining an arrangement to be 'optimum' with a sufficient level of confidence is very questionable. Furthermore, for complex multi-rolled naval vessels, it is not possible to define a whole-boat level performance metric sensibly, and thus an optimum design for performance. Andrews has argued not to search for some optimum for years (e.g. (Andrews, 2013)), but just use such redesigns to give 'insight' and from looking at lots of solutions, select robust solutions. It was thus concluded by the candidate that the proposed generic design synthesis tool should use an approach that should produce arrangements that are 'good enough' but not 'optimised'. This is an application of the decision-making approach coined by Simon (1956)

[1] "Agents" refer to a subroutine that operates on the local level to optimise (in this case) the layout of spaces.
[2] ISA's objective function has been described in detail by Parsons et al. (2008).

as “Simon’s satisficing”. ‘Good enough’ means in this case selecting arrangements that are feasible, realistic and attractive without claiming they are ‘optimised’ beyond this.

From this review it was concluded by the candidate that arrangement ‘optimisation’ using a whole-boat level performance metric for the generation of arrangements for novel vessels, such as SSH(N)s, would be inappropriate. It was considered that if a genetic algorithm like ISA’s was employed to generate ‘good enough’ arrangements, the inherent uncertainty that would come from incorporating novel physical features, would in all likelihood require the genetic algorithm to utilise a greater degree of mutation between generations than for an evolutionary-type design problem, such as the example of a corvette design described by Parsons et al. (2008). This would increase the possibility that a greater number of generations, and hence excessive computation time, would be required to arrive at a solution.

The Technical University of Delft (TU Delft) have created a tool, which like ISA, uses a genetic algorithm to identify and retain attractive arrangements while being limited by a set of user-defined constraints. It was also described in the Design for Layout State of the Art Report to IMDC 2012 (Andrews, et al., 2012). Arrangements that are deemed to be more attractive than others meet a greater proportion of high-level whole-boat design objectives that are user-defined measures (e.g. maximum ship speed and packing density). These measures can be set up for each design as user inputs – unlike the ISA ‘black box‘. Thus unlike ISA, which uses an objective function (based on layout ‘efficiency’), TU Delft’s tool will generate a set of arrangements that meet a number of high-level design objectives, and could be considered ‘good enough’. Like ISA, through multiple iterations (i.e. generations), the Delft tool focuses on arrangements which maximise some user-defined function at the local level. Variations in the generated arrangements come from mutations in the genetic algorithm. This affects the order in which objects are arranged by a packing algorithm, which has been described by van Oers et al. (2009). Furthermore, unlike ISA, TU Delft’s method has two steps in its search for solutions (Andrews, et al., 2012). Firstly, it identifies arrangements that are naval architecturally balanced at a concept level, and then it searches for preferred arrangements that meet some high-level design objectives. It was concluded by the candidate that an approach devised to produce ‘good enough’ arrangements suitable for the exploration of novel concepts, such as SSH(N)s, could be similar to the first step of the Delft tool.

For a submarine concept, it was considered by the candidate that the ISA’s HGA-MAS ‘agents’ would not have influenced a submarine arrangement due to the low number of spaces for each Zones-deck, and thus, the agents would be heavily constrained by the space being fixed by ISA. Some large space containing objects, such as diesel generators and objects whose location is critical on the global (whole-boat) level, such as the bridge, are fixed *a priori* in ISA, as demonstrated by Parsons et al. (2008). This is in contrast to TU Delft's tool, which has relative locations for key spaces allocated early in the arrangement process (by rules defined by the designer). By allocating large spaces to specific Zones-decks without any ability for the designer to rearrange, these objects are effectively bounded in their Zones-decks by hard constraints. Hence, it has been concluded by the candidate that ISA would struggle to produce a sufficiently diverse selection of styles needed for the proper concept exploration of novel submarines. The Packing Approach in Delft's tool, however, does not always rigidly enforce hard constraints, which could be vital in a submarine design's arrangement, due to the sensitivity of submarine arrangement to the various aspects involved to achieve the naval architectural balance of a submarine.

Andrews (1981) proposed design synthesis should commence with the disposition of major spaces in the ship, to both initially size a ship and select hull dimensions and form. This 'inside out' approach allows the consideration of different layouts within a hull while dimensions that are still to be fixed. The TU Delft tool similarly uses this 'inside-out' approach. The major objects are initially located, followed by the ship topside being 'wrapped' around a layout. ISA, in contrast, arranges its spaces in an 'outside-in' approach. The spaces are positioned into a rigidly pre-defined hull that is fixed first by ASSET. It was concluded that this precludes the possibility of performing minor alterations to encase a layout completely, although this may result in the hull form having excellent hydrodynamic performance characteristics, even if other aspects may be compromised. Thus, it was concluded that ISA suffers from the inability to consider the holistic synthesis of the vessel.

ISA is not based on truly three-dimensional modelling of arrangements, which would have helped identify potential overlapping between the hull and the layout of internal spaces or between individual Zone-decks. ISA attempts to minimise these overlaps by the construction of the objective function used by the 'agents' that direct the geometry and topology of spaces with each Zone-deck. In contrast, the TU Delft geometric arrangement packing approach operates in three-dimensional space at a whole ship level (unlike ISA's sub-optimised zones). The Packing Approach seeks to minimise the overlap in objects by shifting them and placing them in volumes of free space (van Oers, et al., 2009). TU Delft's tool also allows the (minor) alteration of the hullform to include objects protruding from the hull. From this, it was concluded that the inside-out approach used by TU Delft's tool was superior to ISA. Any proposed approach to the generation of arrangements for early stage concepts, such as SSH(N)s, should also incorporate a synthesis of hull and layout.

The parametric geometrical modelling mentioned by van Oers et al. (2009) and Andrews et al. (2012), which in a feedback loop defines the shape of the hull in TU Delft's tool, can be altered by the genetic algorithm, to accommodate the emergent three-dimensional arrangement geometries. This feature would require constraining any investigation into SSH(N) concept designs if the proposed generic design procedure based on Burcher & Rydill (1994) was to be followed. The pressure hull geometry would need to be initially specified before synthesising the design (including arrangement). Due to the sensitive nature of achieving naval architectural balance for submarine concept designs, it is considered by the candidate that major structural features, such as the pressure hull diameter, would not be easily altered without affecting the overall design of a concept. This is because other design features, such as the trim tanks, would then need to be re-sized. This was considered computationally inefficient and inappropriate. It was concluded from the review that the TU Delft Packing Approach should not be adopted for use in investigating submarine concepts, such as SSH(N)s.

2.5.4 DESIGN BUILDING BLOCK APPROACH

The Design Building Block (DBB) approach was introduced by Andrews and Dicks (1997). DBBs can have both geometric, physical and operational characteristics assigned to them and be assembled to form a geometric arrangement. Unlike ISA and TU Delft's tool, the DBB approach has its genesis rooted in submarine design, as evidenced by the development of SUBCON (Andrews, et al., 1996). GRC QinetiQ (2015) have developed the computer suite Paramarine that has a DBB capable module (SURFCON) that can be used 'off the shelf' with other submarine modules to architecturally synthesis submarine concepts. Thus, a DBB approach should be easier to interface with when creating a computer-based tool, which is capable of producing generic submarine concept designs. Furthermore, the DBB approach has already been demonstrated by Pawling and Andrews (2011) to be able to generate several concept level designs of an SSH(N) concept.

Using its naval architecture analysis modules, Paramarine can audit a concept design and determine performance with respect to (say) powering and stability. The audit can reveal design infringements that require the designer to adjust the design and is thus not a 'black box' decision process. Andrews et al. (2012) commented that the designer could acquire knowledge relating to generating acceptable arrangements for concept designs by directly modifying a design study and improving its arrangement. The acquisition of the same knowledge was not considered readily available to the designer when using a genetic algorithm approach. According to the rules set up in a genetic algorithm approach, once a genetic algorithm produced arrangement is generated, it is not intended to be subsequently modified by the designer. Rather, modification of a ship's general arrangement occurs 'naturally' downstream through the evolution of subsequent generations due to the genetic mutation process, not the designer's intervention. This 'static' nature of such ship arrangement generation means that insights, such as reasons for a given arrangement being invalid by exceeding the space available to pack in compartments, could be readily recorded by a computer program governing the genetic algorithm. However, reliably guiding a genetic algorithm by avoiding whole-boat (i.e. emergent) levels of invalidity, such as poor access or demands impinging on the overall design (e.g. stability), would need to be done by providing a constraint facility on the genetic algorithm and/or the objectives, as investigated by Duchateau et al. (2015). It was considered that it was highly questionable as to whether a computer program could be created to record the reasons why an arrangement is invalid at the whole-boat level, and hence, provide direction to the genetic algorithm-based tool. Thus, the knowledge gained from the experience of 'manually' modifying an arrangement, risks being lost or not even appreciated by the concept designer. For example, Duchateau et al. (2015) only recorded those performance criteria that were not met by each arrangement but not the reasons why this occurred.

Paramarine has powerful design analysis tools, which together enable a concept design to be naval architecturally audited for the achievement of sufficient design balance. It was considered ideal to create and assess a handful of concept designs. However, if arrangement iteration is to be performed 'manually', as in the current DBB approach using Paramarine[1], achieving a very high number of concepts ($>10^2$) was considered to be highly impractical. The expected wide range of possible configurations for SSH(N) designs meant utilising Paramarine would require an excessive amount of time to complete a wide-ranging design exploration. It was however concluded to be well suited for validating a smaller selection of designs of interest, produced from an

[1] However, UCL DRC has now produced a simpler architectural synthesis tool (Pawling, et al., 2015) that has some layout rules.

initially wide number of options and those could then be further developed for refined naval architectural balance in subsequent stages of the design process.

The SUBCEM tool created by van der Nat (1999) uses “objects” which are very similar to the UCL DBBs. These objects are then arranged into specific spaces called “cells”, which are similar to the Zone-decks in ISA. However, each SUBCEM cell can be defined dynamically, depending on the characteristics of the objects to be allocated to it. Objects are allocated to cells by the designer using a tool called SUBSPACE. This makes SUBCEM similar to Paramarine with human input required for arrangement generation; however, SUBCEM is partially automated with the local optimisation of the placement of an object (i.e. compartment) arrangement within a cell. This can improve the speed of localised packing of compartments, but is not the global approach of the later TU Delft Packing Approach (van Oers, 2011). In SUBCEM, the arrangement of objects is driven by topological knowledge obtained before the specific design commences. Van der Nat (1999) observed that it is advantageous to define the location of objects relative to one another but not specific to the overall structure of the design. This is said to be because is removes the requirement to specify topological information which may not yet be available. Van der Nat remarked the penalty for using relative locations of objects is the lack of a guarantee that arrangements will be valid. Nonetheless, this was noted as a possible approach to submarine arrangement design, when addressing the novelty of UUVs in SSH(N)s.

The TU Delft tool (van Oers, 2011) is similar to UCL’s DBB approach and the SUBCEM tool by van der Nat (1999), as it creates objects with assigned characteristics, however unlike the UCL and van der Nat’s approach; the TU Delft tool produces the object’s position via a computer-based algorithm. The arrangement algorithm is controlled by a genetic algorithm designed to identify the order in which spaces should be allocated. This suggests that it is possible to generate an arrangement using highly automated computer tools that require minimal human direction. However, if optimisation is desired, the designer using this tool ought to know what is the basis of the optimisation process in the TU Delft tool and whether it is appropriate to a given submarine arrangement. The likelihood that the submarine designer would lack this knowledge is considered further evidence that arrangements generated with minimal human direction cannot be ‘optimised’ in a consistent and design specific manner if the basis is generic.

2.5.5 CONCLUSION ON STATE OF THE ART ON ARRANGEMENT TOOLS FOR NOVEL DESIGNS

It was concluded that none of the existing approaches were capable of fulfilling the requirements of a highly automatic and 'generic' approach, which was seen to be necessary to provide a wide-ranging investigation of the unrefined solution space for potentially unorthodox SSH(N)s. While there are only a few, architecturally focussed design tools that have been discussed (summarised in Table 3), none was considered to meet sufficiently the needs to investigate the SSH(N) concept. Instead, aspects drawn from the approaches used in these tools were drawn on to construct a bespoke arrangement tool that could be used within the proposed 'generic' submarine design tool identified as required for SH(N) investigations in Section 2.4. Such an arrangement tool would require input from the mathematical modelling of objects, similar to that described by van der Nat (1999), to generate some DBB characteristics to meet a set of top-level submarine performance characteristics. A computer-based arrangement disposition algorithm, similar to the one outlined by van Oers (2011), was considered necessary to produce a wide range of concept design layouts, and van der Nat's (1999) approach was considered to indicate that relative object locations could be used to address novel arrangements, such as accommodating UUVs in SSH(N)s.

Although the disposition algorithm of the TU Delft arrangement tool, outlined by van Oers et al. (2009), was attractive it was not considered to be readily adoptable for submarine design. The Packing Approach put forward by van Oers (2011), does not always rigidly enforce hard constraints, which could be vital in a submarine design's arrangement, due to the naval architectural balance sensitivity resulting from arranging various elements in a submarine (Burcher & Rydill, 1994). However, the TU Delft approach has been shown to be capable of producing arrangements for feasible and attractive ship designs (rather than being 'optimised' to a single 'best' design) (Duchateau, et al., 2015) and (Andrews, et al., 2012). However, using Paramarine a DBB approach can produce feasible submarine designs (Pawling & Andrews, 2011). It was therefore concluded that it was attractive to devise an arrangement approach, using DBBs, to perform 'automatic' arrangements (unlike Paramarine's 'manual' allocation of DBBs). It was acknowledged that such a (nominally) 'automatic' arrangement approach would still require some initial designer input. This would be logically upstream from performing the arrangement of compartments, by specifying (say) the constraints on the location of tankage or particular option-specific constraints. The UoM's ISA genetic algorithm basis was not considered appropriate due to the difficulty in defining a robust yet adaptable whole-boat level objective function for the wide range of potential SSH(N) concepts. Essentially, it would not be possible to be assured that any generated SSH(N) concept design was 'optimum'. A broad range of conceivable designs ought to be considered in an extensive exploration of the unrefined solution space for a new concept, such as an SSH(N). To date, only Nordin (2014) has achieved this by a series of weighted OA scenarios focussed on a very narrow solution space[1], and so was thus considered inappropriate for use in concept exploration of SSH(N)s, intended for a wide range of operations and exploring the submarine design impact of future UUV technologies.

2.6 THE RESEARCH PROPOSAL

Following the State of the Art review, the following proposal has been formed:

To devise and demonstrate an approach which can produce the refined solution space within a practical timeframe, for the 'conventional' concept exploration of novel submarine concepts.

2.7 OBJECTIVES TO CONFIRM THE PROPOSAL

2.7.1 THE GENERIC SUBMARINE DESIGN TOOL

From the discussion in Section 2.3, the proposed submarine design tool should be used to populate the unrefined solution space to meet the research proposal to produce the refined solution space. Section 2.3 concluded that the tool should produce discrete designs that are architecturally descriptive.

Van der Nat (1999) considered that the process of designing new submarines had traditionally been explored and analysed in two ways: either building on a preferred existing design ('evolved design'), or a much more time consuming and resource intensive development of a noticeably new design. These represent two extremes on a continuum of resources expended and knowledge captured from reviewing new designs. Van der Nat proposed a tool to provide "fast and flexible" concept generation and analysis. His SUBCEM tool was intended sit in a 'gap' in this continuum and be flexible in a manner spelt out in the definition he provided. It is intended for the proposed generic submarine design tool to similarly sit in this 'gap' and be flexible. However, unlike SUBCEM, the proposed tool ought to be capable of considering a range of design styles – including unorthodox ones. This would give the proposed tool a greater degree of flexibility.

[1] Specifically, Baltic Sea operations using a style of submarine design very similar to Kockum's current SSK design.

For the case of the novel payload, new knowledge needs to be obtained relating to UUVs carried by potential SSH(N)s. This was proposed to be achieved using Operational Analysis (OA). From Section 2.4 it has been proposed that this generic submarine design tool should be capable of generating the wide variety of potential designs in the unrefined solution space for a novel vessel, such as an SSH(N). Section 2.5 also identified a need for a computer-based compartment arrangement approach to be used within the proposed tool. This arrangement approach needs to be highly automated. However, it was also considered that the generic submarine design tool should also be partially driven by the designer and be capable of being interrogated i.e. not be a 'black box' tool. This was considered necessary to ensure that the process used by the tool can be examined to verify that the process and the assumptions used by the tool are valid and appropriate for the designs being investigated.

2.7.2 THE APPROACH PROPOSED FOR EXPLORING THE UNREFINED SOLUTION SPACE

Section 2.4 concluded that the proposed approach should be facilitated by a 'generic' submarine design tool. This tool should be able to synthesise a range of concept designs with potentially differing styles – ensuring an extensive exploration of the unrefined solution space. Section 2.3 concluded that a system of metrics should also be devised to determine which concept designs produced were preferred at the concept level of definitions. As the proposed approach should be capable of exploring likely SSH(N) concepts, the approach should be able to define the bounds of the refined solution space for SSH(N) options, by producing the refined solution space from the unrefined solution space. The proposed approach needs to be capable of producing the refined solution space in a practical timeframe. For an extensive investigation of the SSH(N) solution space at a concept phase level of definition, it has been considered this needs to be no more than the order of a few weeks.

2.7.3 TABLE OF RESEARCH PROPOSAL OBJECTIVES

Table 4 shows the collated objectives for meeting the Research Proposal.

Table 4 – Table of Research Proposal Objectives

Objective	Description
	Operational Analysis
1.1	Using operational analysis, obtain new knowledge regarding the nature of the novel payload of UUVs.
	A 'Generic' Submarine Design Tool
2.1	The tool can be used to produce submarine concept solutions in the unrefined solution space.
2.2	The tool should be capable of generating the wide variety of concepts in the unrefined solution space for a novel vessel, such as an SSH(N). The tool needs to be shown to be 'flexible'.[1]
2.3	Need to devise an internal submarine arrangement approach that is highly automated (i.e. computer-based) and able to produce conceivable[2] arrangements.
2.4	The tool needs to be able to be interrogated (i.e. not be a 'black box') so it can be examined and verification provided that the processes and assumptions in the tool's construction are valid[3] for the designs it generates.
	Proposed Approach to Producing the Refined Solution Space
3.1	The proposed approach can address a range of concept designs with potentially differing styles.
3.2	Need to devise metrics ('performance' and cost) that are appropriate in determining 'preferred'[4] concept designs.
3.3	The proposed approach can produce the refined[5] solution space and facilitate 'conventional' concept exploration of novel concepts, such as SSH(N)s.
3.4	The proposed approach can be performed in a practical timeframe of a few weeks.

[1] "Flexible" has been coined be van der Nat (1999) to describe the ability of a submarine design tool to consider additional programmed information, such as for a new technology.
[2] "Conceivable" refers to concept level designs that could be believably naval architecturally balanced by the end of the design process.
[3] "Valid" means that a design is naval architecturally balanced to a conceptual level of granularity
[4] "Preferred" refers to designs deemed attractive by some metric, given all the available information at the concept level of definition.
[5] "Refined" means that a balanced design has been synthesised.

CHAPTER 3 - OPERATIONAL ANALYSIS SIMULATIONS FOR UUV PAYLOADS

3.1 INTRODUCTION

This chapter outlines an Operational Analysis (OA) tool called the UUV Grid Optimisation Tool (USGOT). It was created to provide a measure of effectiveness (MOE) for various potential UUV fleets that could be deployed from an SSH(N). The output would then provide the designer of an SSH(N) concept with payload characteristics.

The chapter explores the Concept of Operations (CONOPs) for a UUV fleet carried by an SSH(N). The OA tool mathematically models a range of possible deployments considered typical of a fleet of UUVs and uses an energy minimisation approach to produce 'optimal' UUV deployments for a set of operational scenarios. Three representative scenarios, which are considered to be amongst the most resource demanding and hence likely to have the greatest impact on an SSH(N)'s design, are outlined in this chapter and used in USGOT's simulations. From the results of the USGOT simulations of the three representative scenarios, a mix of UUVs to be deployed from a putative SSH(N) was obtained.

3.2 A FLEXIBLE OPERATIONAL ANALYSIS TOOL

3.2.1 THE OBJECTIVE OF AN OPERATIONAL ANALYSIS TOOL FOR UUVS

In order to achieve the capability and benefits for UUVs described in Section 1.2, the UUVs must be hosted on a suitable submarine, with a key consideration being the number of required UUVs to perform a set of missions. This payload provides a major determinant of the SSH(N)'s hotel power and payload volume requirements. Pawling & Andrews (2011) stated that future submarine designs could be driven by the number, power requirements and payload of the hosted UUV fleet. Throughout the design process of an SSH(N), the interplay between the UUV payload demands and the propulsion and overall power demand of the SSH(N) is expected to be significant. However, the total submarine power demand would be less important if power is provided by the 'limitless' energy of a nuclear reactor.

The OA tool has to provide a measure of effectiveness (MOE) for various UUV fleets that could be carried on an SSH(N), as a prerequisite for constructing the proposed 'generic' submarine design tool. Pre-calculating the effectiveness of a limited number of UUV fleets using USGOT, before undertaking the holistic design of

SSH(N)s, avoids the need for very large and computationally demanding batch runs of many possible combinations of UUVs every time an SSH(N) concept is generated by the proposed 'generic' submarine design tool.

The characteristics of the UUV payload have additional implications for the design and layout of the SSH(N). In addition to the volume and weight demands of the UUV payload itself, it has already been remarked on by Purton et al. (2013a) that the number and composition of UUVs carried would also affect the portion of an SSH(N)'s volume devoted to housing and performing maintenance of the SSH(N)'s UUV fleet. Thus, an example of such an additional demand would be the number and size of the UUV Launch and Recovery Systems (LARS) incorporated into the SSH(N) design. Some possible LARS concepts for UUVs have been explored to a limited extent in Appendix A[1].

3.2.2 CREATING AN OPERATIONAL ANALYSIS TOOL FOR UUVS

A suitable OA tool for a UUV payload was not available– thus, it was concluded that one had to be created, although there has been some limited work on which to base the OA tool. Binns et al. (2011) presented some OA on a homogenous UUV fleet. However, the OA was limited and furthermore, Binns et al. did not outline the modelling approach used. Some modelling equations published by MIT (2000) were adopted in combination with the information drawn from Binns et al., as a basis for constructing mathematical models to describe UUV operations. Furthermore, a proposal from the US DARPA to use large 'Mothership' UUVs to deploy smaller UUVs (Maxey, 2013) concluded that UUV operations would be undertaken using a variety of UUVs. It was thus concluded that the USGOT tool should be capable of considering heterogeneous UUV payloads. As already discussed in Section 1.2, UUVs were conveniently classed into three categories. It was thus assumed that a heterogeneous UUV payload would consist of a number of one type of UUV from each of these three categories.

It was considered that the OA tool should be 'flexible' enough to address the wide range of UUVs, which might make up the UUV payload of an SSH(N). Furthermore, since UUVs are an evolving technology (Evans, 2010), the typical design characteristics of UUVs likely to be deployed by an SSH(N) are not yet fixed. It was thus

[1] Appendix A presents a short description of some UUV LARS concepts and SSH(N) configurations from the current research. These are only 'sketches' and not validated concepts.

concluded that rather than basing the UUVs to be carried on specific existing designs, which are likely to be obsolete by the time the SSH(N) might come to fruition, it was sensible to assume believable UUV characteristics based on extrapolating from current trends. Furthermore, the UUV design characteristics used in UGSOT models are not for design purposes – they merely indicate likely UUV performance. An example of the parameters inputted into the USGOT tool used to define the largest assumed UUV type (Category A UUV) is shown in Table 5. These parameter values are only predictions and as such, this UUV does not currently exist.

Table 5 – Example of Parameters for a Category A UUV used in a USGOT Simulation

Parameter	Value
Submerged Displacement (VD) [kg]	10,000
Bluff Body Area (A) [m^2]	2.035
Transit Speed for Maximum Range (TSo_{pt}) [knots]	4.0
Sprint Reserve Factor (SRe)	1.2
Minimum Transit Distance (TD_{min}) [nm]	20
Maximum Transit Distance (TD_{max}) [nm]	400 (Calculated)
Minimum Maintenance Time (MT_{min}) [hours]	5
Maximum Maintenance Time (MT_{max}) [hours]	25
Minimum Endurance Time (ET_{min}) [hours]	5
Maximum Endurance Time (ET_{max}) [hours]	240
Minimum Transit Speed (TS_{min}) [knots]	1
Maximum Transit Speed (TS_{max}) [knots]	8.0
Sensor Range Threshold [nm]	200

A survey of UUVs was conducted to scope the range of UUV design characteristics that USGOT should address. The data on UUVs used in this survey is provided in Table B1 in Appendix B[1] Section B.1. This data was also used to obtain trends likely for the design of future UUVs, from which believable UUV characteristics could be generated. These trends are detailed in Appendix B Subsection B.2.4.

[1] Appendix B presents in detail the 'theory' that is applied to construct USGOT. This includes explanations of the equations derived for creating the tool and a presentation of the source data collected on UUVs.

3.3 CONCEPT OF OPERATIONS

A Concept of Operations (CONOPs) was produced to construct an OA tool for UUVs, to provide the metrics to define the effectiveness of a UUV payload. UUVs have been assumed operationally effective once they are on-station. A DARPA proposal (Maxey, 2013) for 'Mothership' UUVs to deploy smaller UUVs implies that UUVs might employ a multi-stage on-station deployment. It has thus been assumed that the large Category A UUV/MUVs, (defined in Section 1.2), would take the role of these 'Mothership' UUVs acting as hubs around which smaller Category B and C UUVs could cluster. This deployment is illustrated in Figure 6. This deployment pattern is used in all USGOT's scenarios – however, UUV positions are different between scenarios, dependent on each scenario's CONOPs.

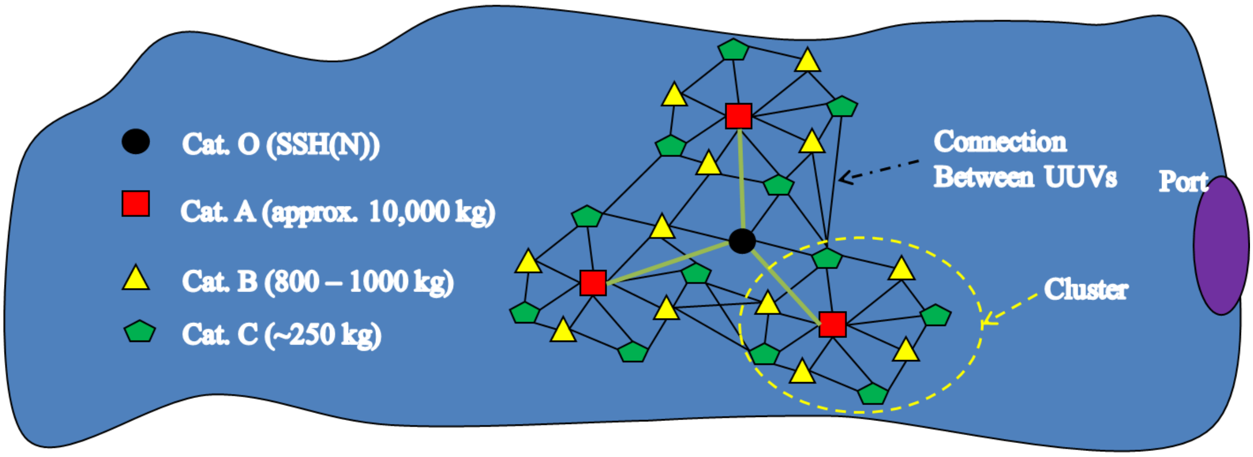

Figure 6 – Multi-Stage UUV On-Station Deployment

A multi-stage deployment pattern, such as that in Figure 6, has the potential to extend the range (i.e. coverage) of the on-station deployed UUVs compared to a single-stage deployment pattern with all UUVs clustered around the SSH(N). In a multi-stage deployment, the on-station UUVs could be considered a net, consisting of local clusters of interconnected UUVs away from the SSH(N) and capable of communicating with each other. A multi-stage deployment pattern would also mean that the on-station deployment of the larger Category A UUVs could provide recharging points for the smaller Categories B and C UUVs. This configuration underpins the mathematical description of operations used in USGOT and is illustrated in Figure 7.

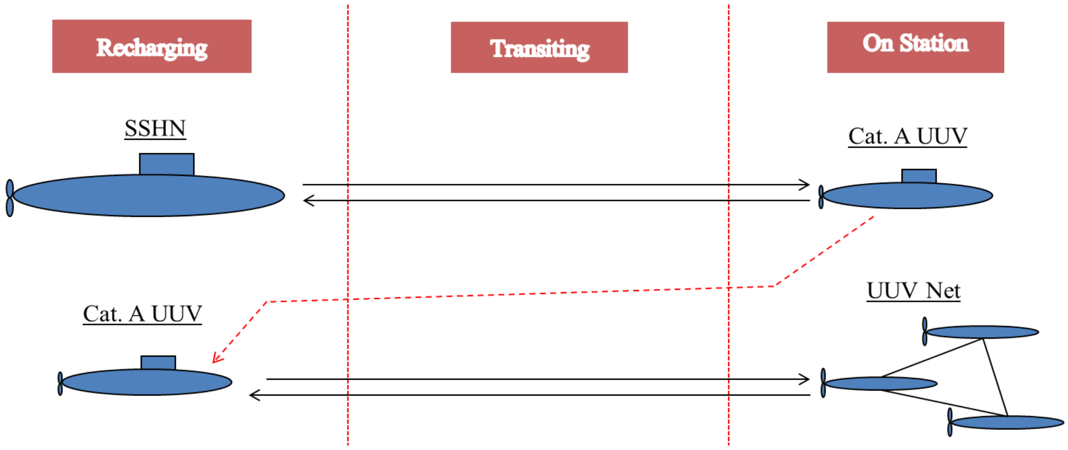

Figure 7 – Illustration of the Operational System

UUV operations have been modelled by a system of UUVs at different operational states: recharging and data transfer; transiting; and patrolling on-station. This means that the rate at which UUVs could come on-station would be equal to the rate at which they go off-station. However, this arrangement cannot be immediately set up following the arrival of an SSH(N) into theatre. Nevertheless, a proposed set of UUV operations by the United States Navy (2004) Unmanned Underwater Vehicles Master Plan 2004, which has been used as the main source for providing UUV CONOPs for this current research, supposed an SSH(N) would always deploy a UUV fleet before taking action.

3.4 MATHEMATICAL ‘OPTIMISATION’ OF A UUV PAYLOAD

3.4.1 INTRODUCTION

The terms “‘optimise’” and “mathematical optimisation” have been used in the current research to describe the manner in which a value that has been maximised (or minimised), from a set of mathematical equations, such as the ones used in USGOT. The utility of optimisation in design is limited both by the degree to which a mathematical model (which must be defined beforehand) represents reality and by the ease with which some Measure of Effectiveness (MOE) can be defined. Given the uncertainties in future UUV technologies and operations, mathematical optimisation is thus of limited use.

USGOT has been used to ‘optimise’ the deployment of a fleet of UUVs, meaning they would be configured in an efficient manner (i.e. a deployment with a high MOE value) when undertaking specific operations. It was recognised that mission optimisation would be complex and dependent on a number of factors, some of which are likely to be beyond the scope of USGOT. However, the equations that model the deployment of UUVs are amenable to mathematical optimisation provided the MOEs are realistic. Thus, the UUV fleet can be assessed to some degree.

The mathematical optimisation of a UUV fleet by USGOT has been calculated in two parts. Firstly, the number of UUVs that are on-station and their individual Radii of Operation (ROO) are maximised in the second stage in Figure 8, using an equation devised specifically for USGOT (and written as a computer program) called the Payload Calculator. This can be considered as a means of 'optimising' the configuration shown in Figure 7.

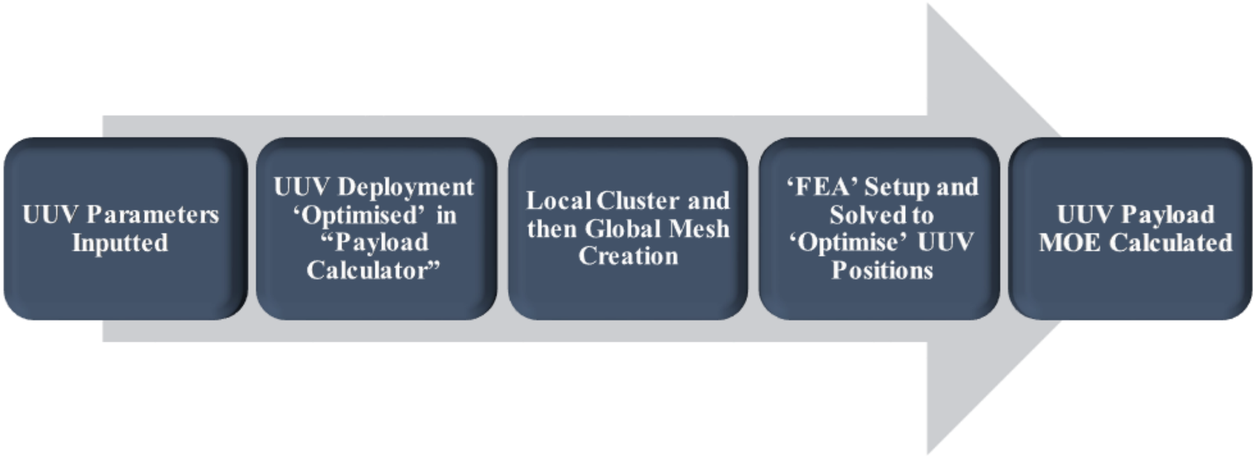

Figure 8 – The Stages of USGOT

The second part is the 'optimisation' of the locations of the individual on-station UUVs, whose numbers and ROO have been 'optimised' by the second step of Figure 8. The second part of 'optimisation' is performed by considering the net of UUVs (see Figure 6) to be analogous to a mesh of truss type elements[1] in an FEA calculation. 'Optimisation' is then achieved by minimising the elastic energy stored in elements in the analogous FEA arrangement. The creation of the mesh of elements is the third step in Figure 8 and the setup and solution of the 'FEA problem' the fourth step in Figure 8. In the fifth and final step in USGOT, a score for the 'optimised' UUV net (which is mission dependent) is calculated. This score is considered to be the MOE for the UUV payload in undertaking a specific operational mission, and so that MOE can be used as a major input to the rest of the SSH(N) concept design.

[1] According to DeepSoft LLC (2008) "*Truss elements are long and slender, have 2 nodes, and can be oriented anywhere in 3D [or 2D] space. Truss elements transmit force axially only and are 3 DOF [Degrees of Freedom] elements which allow translation only and not rotation. … they are used for linear elastic structural analysis"*

3.4.2 'OPTIMISING' THE DEPLOYMENT OF UUVS (THE PAYLOAD CALCULATOR)

3.4.2.i Description of the Payload Calculator

The Payload Calculator enables the calculation of the MOE 'score' (φ). This is the product of the number of UUVs on-station for each of the categories of UUV (Ns), and the transit distance (TD) from the SSH(N) to the operational location for a given scenario. Maximising φ was considered to be the basis of 'optimising' the deployment characteristics of the specified category of UUVs. The score, φ, is a function of the Endurance Time (ET), which is the time a UUV can spend on-station, the Maintenance Time (MT), which is the time a UUV is recharged and repaired, and the transiting speed relative to the cruise speed (α). The Payload Calculator is outlined in this section and is presented in more detail in Appendix B Section B.2.

From the description of the score, φ:

$$\varphi(\mathrm{ET},\mathrm{MT},\alpha)=\mathrm{TD}[\mathrm{N_s}] \qquad \text{[Eqn. 1]}$$

The transit distance (TD) is based on how far a vehicle can travel on the estimated stored energy divided by coefficient of drag (C_d) though seawater of density ($\rho_{SeaWater}$) taken as 1.0275 [te/m^3] for the given set of vehicle properties of displacement (VD), bluff body area (A), propulsion system efficiency (η), actual transiting speed relative (TS_{opt}) to the speed for maximum range (α). Additionally, a fraction of reserve energy (SRe) was allowed for in the calculation to allow for any repositioning on-station and oceanic conditions.

A full description of how the equations for the Payload Calculator have been constructed can be found in Appendix B Sections B.1 and B.2. The key equations are stated here.

The Transit Distance (TD) is expressed as:

$$\mathrm{TD}=\left(\frac{\alpha\ \mathrm{TS_{opt}}}{2(1+0.5\alpha^3)}\right)\left(\frac{c_1\ \mathrm{VD}}{\rho_{SeaWater}\mathrm{A}\eta^{-1}\left(\mathrm{TS_{opt}}\ \mathrm{SRe}\right)^3}-\mathrm{ET}\right) \qquad \text{[Eqn. 2]}$$

The number of on-station UUVs (N_s) for a given type of UUV is expressed in full by:

$$\mathrm{N_s}=\frac{\mathrm{N_T ET}}{\mathrm{LR}}\left(\left(c_3\left(\frac{\mathrm{N_T MT}}{\mathrm{LR}}\left(\frac{\left(\frac{\alpha\ \mathrm{TS_{opt}}}{(1+0.5\alpha^3)}\right)\mathrm{K_1}}{\alpha \mathrm{TS_{opt}}}+\mathrm{ET}+\mathrm{MT}\right)^{-1}\right)^{c_2}+c_4\right)+\frac{\mathrm{K_1}}{1+0.5\alpha^3}+\mathrm{ET}\right)^{-1} \qquad \text{[Eqn. 3]}$$

Where K_1 is a collection of terms to simplify the calculation of Eqn. 3:

$$\mathrm{K_1}=\left(\frac{c_1\ \mathrm{VD}}{\rho_{SeaWater}\mathrm{A}\eta^{-1}\left(\mathrm{TS_{opt}}\ \mathrm{SRe}\right)^3}-\mathrm{ET}\right) \qquad \text{[Eqn. 4]}$$

The values for the constants used are:

$$c_1=3297600\left(\frac{\mathrm{J}}{\mathrm{kg}}\right);\quad c_2=3.0;\quad c_3=5\times3600=18000(\mathrm{s});\ c_4=5\times3600=18000(\mathrm{s});\ \mathrm{LR}=1.1;$$

Further justification on the constants used, including how they have been obtained, can be found in Appendix B Subsection B.4.3. Eqn. 1 is thus expressed by combining the above expressions for its two constituents TD and N_s:

$$\varphi(ET,MT,\alpha) = -\left(\frac{\alpha\, TS_{opt}}{2(1+0.5\alpha^3)}\right)\left(\frac{c_3\ VD}{\rho_{SeaWater} A\left(TS_{opt}\ SRe\right)^3} - ET\right)$$
$$\times\left\lfloor \frac{N_T}{LR}\left(\frac{ET}{MT+\left(\frac{1}{(1+0.5\alpha^3)}\right)\left(\frac{c_3\ VD}{\rho_{SeaWater} A\eta^{-1}\left(TS_{opt}\ SRe\right)^3} - ET\right)+ET}\right)\right\rfloor \qquad \text{[Eqn. 5]}$$

3.4.2.ii Demonstration of the Payload Calculator

A payload of 10 Hugin 1000 UUVs (Kongsberg, 2012) has been simulated in the “Payload Calculator” to demonstrate and verify the tool. The value for Maintenance Time (MT) was kept constant at 5.0 hours to simplify the calculation by using only two variables (ET and α), as it was found that the effect of MT following numerous sensitivity simulations was negligible for minor variations (less than 20%) to the value for MT. Physical constraints were applied to bound the search space using the Payload Calculator. These physical constraints were applied to ensure that the solution found would be operationally conceivable. The physical constraints placed on the simulation are as follows:

$$0.5 \leq \propto \leq 1.5 \text{ i.e. } 2.0 \text{ knots} \leq TS \leq 6.0 \text{ knots}$$

$$10 \text{ hours} \leq ET \leq 24 \text{ hours}$$

$$MT \equiv 5 \text{ hours}$$

The characteristics for this UUV, as described in Table 6, were inputted into the Payload Calculator.

Table 6 – Hugin 1000 (3000m Variant) Specifications (Kongsberg, 2012)

Parameter	Value
Country	Norway
Manufacturer	Kongsberg
Vehicle	Hugin 1000 (3000m Variant)
Length [m]	5.0
Diameter [m]	0.75
Max. Cross Sectional Area (A) [m^2]	0.44
Max. Dive Depth [m]	3000
Weight (VD) [kg]	850
Stored Energy (E_{Total}) [kWh]	15.0*
Max. Speed [knots]	6.0
Max Endurance [Hours]	24
Speed for Max. Range (TS_{opt}) [Knots]	4.0
Max. Range (TD) [nm]	71.8*
Coefficient of Drag (C_d)	0.0388*

N.B. * = Calculated Value Using UUV Trends

The part of Eqn. 5 computing Transit Distance (TD) produces a smooth continuous function (see Figure 9). However, the part of the Eqn. 1 that calculates the number of UUVs on-station (N_S) is not continuous as N_S is calculated and rounded down to the nearest integer, as it is physically impossible to have only part of a UUV on-station.

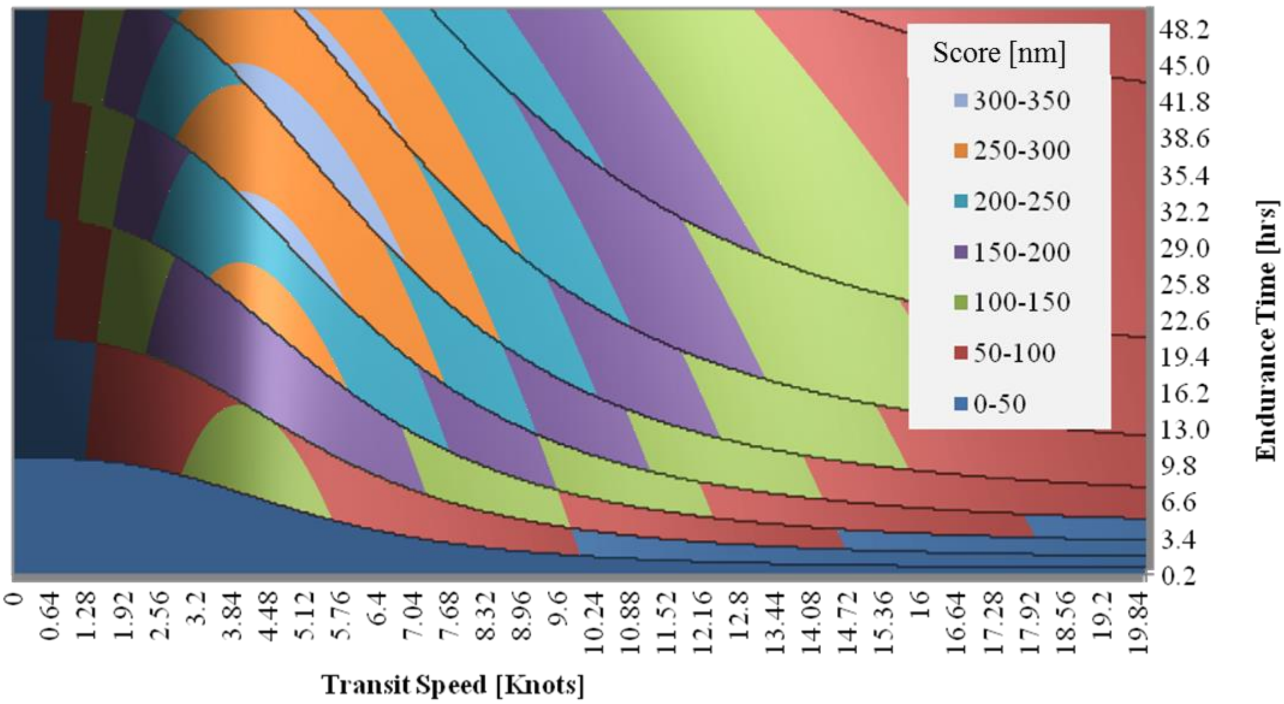

Figure 9 – Transit Speed and Endurance Time Affecting the Payload Calculator 'Score' for 10 Hugin 1000s

Each ‘step’ in Figure 9 is a result of another UUV coming on-station and for each one of these ‘steps’, there is corresponding maximised values of Endurance Time (ET) and Transit Speed (TS), which can be mathematically obtained. The ‘optimum’ value of φ (and thus considered the best trade-off between TD and N_S), lies on the outside edge of each one of the ‘steps’ in Figure 9, because any small increase in ET and especially TS (i.e. moving away from the ‘edge’ of a ‘step’), would not increase the number of UUVs on station but would decrease the transit distance. The Payload Calculator selects the score (φ) obtainable given the selected physical constraints. The results in Figure 9 show that Eqn. 5 behaves as intended, i.e. it correctly represents the characteristics of the deployment pattern outlined in Figure 7. It was therefore concluded that Eqn. 5 could be used in the Payload Calculator section of USGOT.

3.4.3 ‘OPTIMISING’ THE POSITIONING OF ON-STATION UUVS

The ‘optimisation’ of the positions of the UUVs on-station were configured according to the probability of detection of an opposing vessel by the UUV net to a set of linear link elements in an FEA problem: an ‘optimum’ configuration was then achieved by minimising the stored energy in the analogous FEA set-up.

This solution is based on a score metric, which is the product of the area covered by deploying the UUVs, and the ‘redundancy’ of the UUV net. The scoring metric is called the ‘Equivalent’ Area[1] and is measured in nautical miles squared. The ‘redundancy’ is based on the mean number of points of detection that an opposition vessel on a random vector towards the SSH(N) would be detected by the UUV net and the mean distance of these points from the SSH(N). An individual point is defined by the random vector intersecting with an imaginary line drawn between two connecting UUVs and represents the likelihood of meeting some threshold probability of detecting an opposition vessel. Details on forming the equations that govern the setup and solution of the ‘FEA problem’ are spelt out in Appendix B Section B.3. Furthermore, the equations that deal with the complexity of detection probabilities, involving multiple (more than two) UUVs, are also detailed in Appendix B Subsection B.3.2 as well.

The governing ‘FEA’ equation (Eqn. 6) between two ‘nodes’ (i.e. UUVs) is briefly described here:

$$F_{ij}=-k_{ij}u_{ij} \qquad \text{[Eqn. 6]}$$

[1] ‘Equivalent’ Area is intended to be represent an imaginary area covered by a UUV net, which has a no redundancy. This measure is intended to consider the effects of both the area covered by a UUV net *and* the quality of the arrangement by considering measure of redundancy of a UUV net required to detect an opposing vessel moving through the net.

Where the ‘force’ (F) between nodes i and j is equal to the product of the ‘stiffness’ (k), which is related to the sensor ranges of the UUVs, and the displacement (i.e. distance) squared (u) of the UUV positions. In a UUV net, there is a number (i) of UUVs (i.e. nodes) and each node has a connection to every other node (j). The relationship between each combination of nodes is analogously described by the ‘stiffness’ matrix (k), which has dimensions of i by i. The sum of displacements for a specific node, i, is the overall displacement for that node (i.e. the overall UUV distance the UUV moves from is starting position).

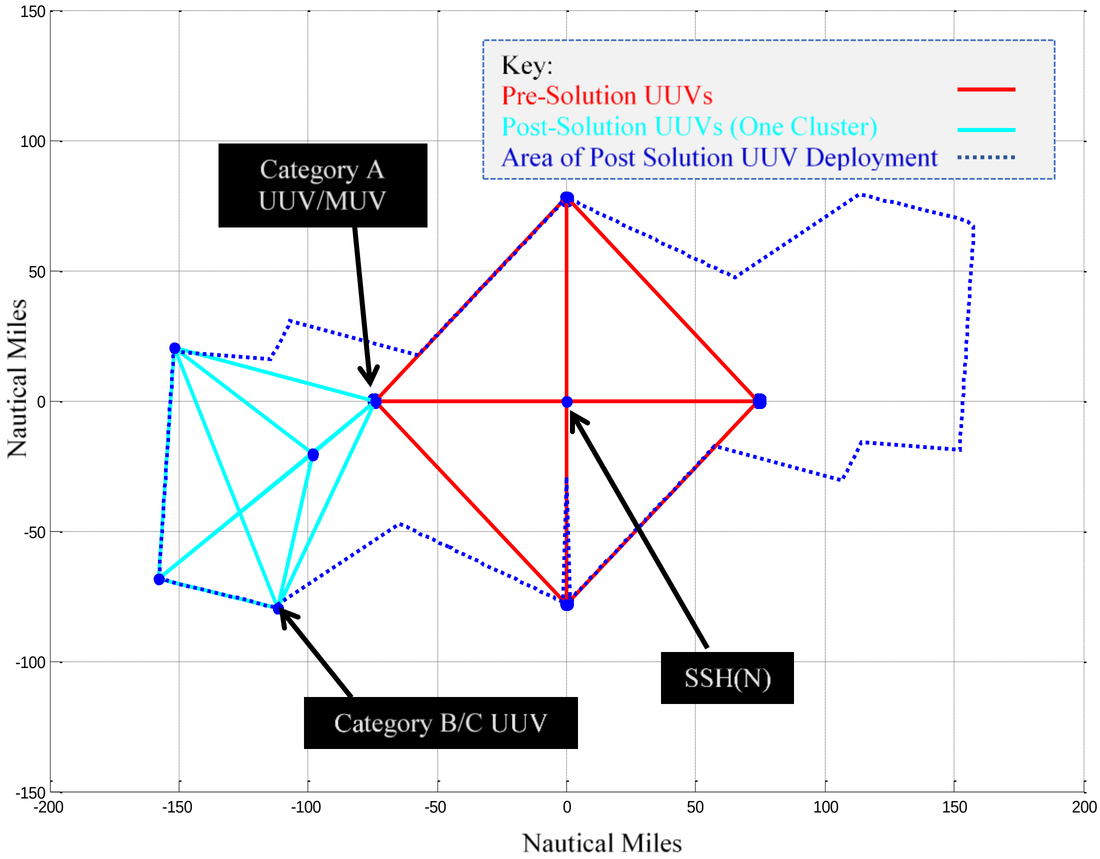

Figure 10 – Simplified USGOT Simulation Showing Four Category A UUV/MUVs On-Station are Part of a UUV Net

A typical USGOT simulation is shown in Figure 10. It shows the UUV net before ‘optimisation’ (i.e. solution) and post-solution. It has been simplified in two ways. Firstly, the UUV positions for only one of four clusters are shown. Secondly, the virtual nodes used to represent the detection probabilities of combining more than two UUVs (explained in Appendix B Subsection B.3.2) have been hidden for clarity. Figure 10 shows the solution the ‘FEA problem’ has caused the area of UUV deployment to increase as intended, and by doing so improved the UUV deployment.

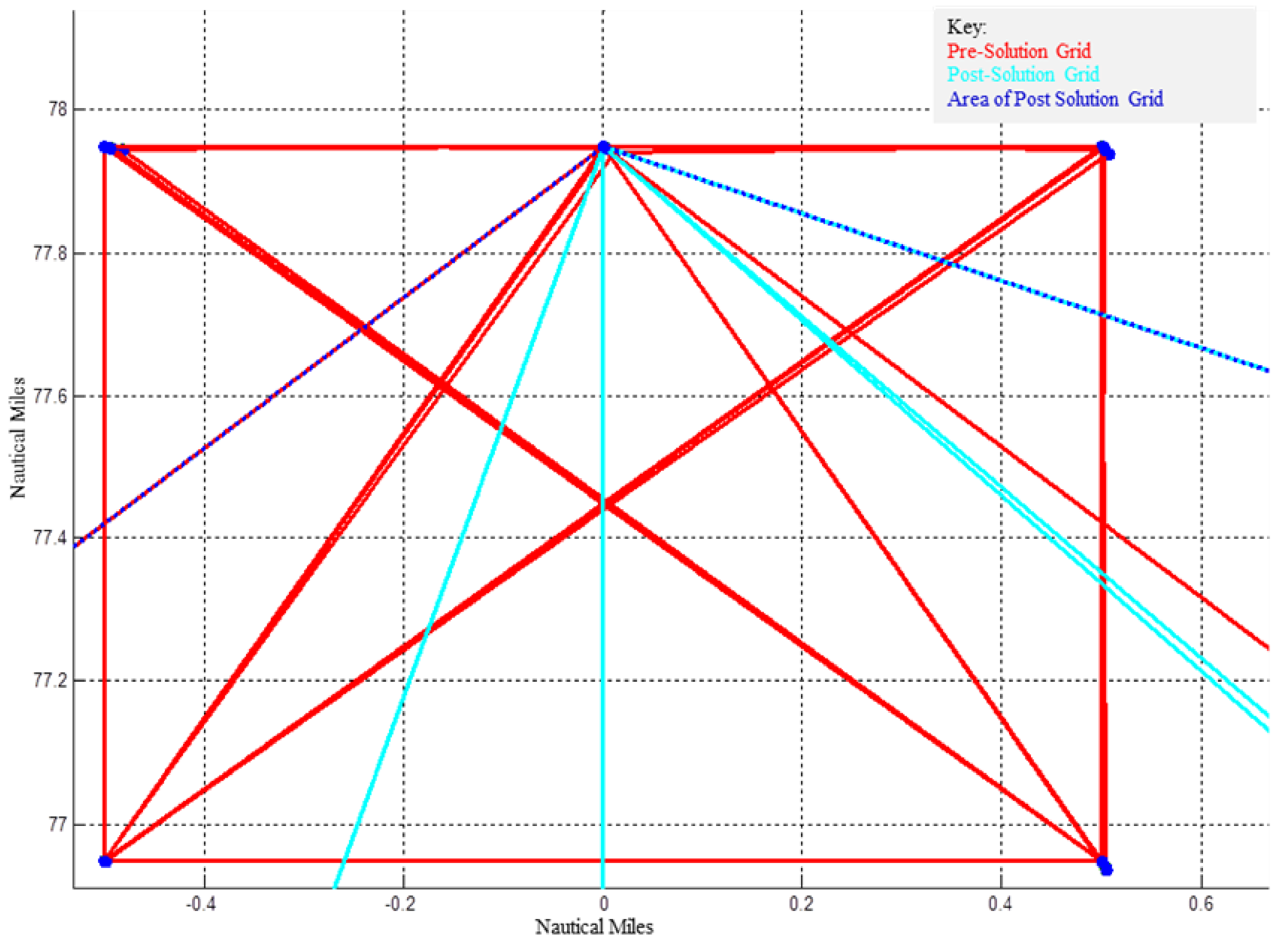

Figure 11 - Typical Zoomed-In View of a Cluster Pre-Solution

To illustrate the setup of UUVs at pre-solution, a zoomed-in view is provided in Figure 11. The Category B and C UUVs in Figure 11 are tightly distributed in pre-solution around a Category A UUV at (0,77.95), with the corresponding virtual nodes adjacent to the real nodes. For example, such a cluster of real and virtual nodes can be seen at (0.5,76.9).

3.5 THREE SIMULATED SCENARIOS SOLVED BY USGOT

3.5.1 RANKING OF POSSIBLE UUV MISSIONS

A set of potential UUV mission types have been identified and prioritised on page 12 of the United States Navy (2004) Unmanned Underwater Vehicles Master Plan 2004, namely:

- Intelligence, Surveillance and Reconnaissance (ISR);
- Mine Countermeasures (MCM);
- Anti-Submarine Warfare (ASW);
- Inspection / Identification;
- Oceanography;

- Communication / Navigation Network Node;
- Payload Delivery;
- Information Operations (IO);
- Time Critical Strike (TCS);

These nine mission types for which UUVs have been ranked in Table 7 for the perceived impact that each mission would have on the overall design of an SSH(N). The rationale has been included to explain how the required UUV payload for each mission is considered to affect an SSH(N)'s design. It was considered that the large numbers of UUVs greatest impact on the SSH(N)'s design would arise from the additional volume demanded on the submarine due to the quantity of UUVs. This could make it difficult to incorporate the UUV payload and its supporting systems into a naval architecturally balanced design, given most modern submarines are volume driven (Burcher & Rydill, 1994). Furthermore, there could be a significant electrical power demand (predicted to be up to approximately 50kW[1]) from such a large UUV payload. For an SSHN, its nuclear reactor should easily provide this electrical power, however, for a non-nuclear SSH, such a power demand could have significant operational and design implications, which reinforces the working assumption of the SSH(N) being nuclear powered.

Table 7 – Ranking of Possible UUV Mission Types According to Considered Impact on SSH(N) Design[2]

<table>
<tr><th>Priority</th><th>Mission Type</th><th>Rationale for Rank</th><th>USGOT Scenario Applicability</th></tr>
<tr><td>1</td><td>Anti-Surface Warfare (ASuW) / Anti-Subsurface Warfare (ASW)</td><td rowspan="2">Several Large Category A UUVs</td><td>1 & 3</td></tr>
<tr><td>2</td><td>Intelligence, Surveillance and Reconnaissance (ISR)</td><td>1 & 2</td></tr>
<tr><td>3</td><td>Communications/ Navigation Network Nodes (CN3)</td><td rowspan="2">Specialist Payload</td><td>-</td></tr>
<tr><td>4</td><td>Mine Countermeasures (MCM)</td><td>2</td></tr>
<tr><td>5</td><td>Payload Delivery</td><td rowspan="2">A Large Category A UUV Needed</td><td>2</td></tr>
<tr><td>6</td><td>Time Critical Strike (TCS)</td><td>2</td></tr>
<tr><td>7</td><td>Oceanography</td><td rowspan="3">Only a Few Smaller UUVs Required</td><td>2</td></tr>
<tr><td>8</td><td>Inspection/Identification</td><td>2</td></tr>
<tr><td>9</td><td>Information Operations (IO)</td><td>-</td></tr>
</table>

It was considered that the lower priority mission types would not have a significant impact on SSH(N) design, which would not be already apparent from the higher priority mission types (Types 1 to 4). The rest of this

[1] Assumption based on a worst-case scenario of simultaneously recharging a fleet of 25 Category B UUVs (e.g. USN's Naval Undersea Warfare Centre "Mid-sized Autonomous Research Vehicle" UUV) at 2kW per UUV (Malay, 2015)
[2] Mission Types defined in USN's UUV Master Plan 2004 (2004)

section outlines three scenarios, which are considered plausible and gives the range of UUV payloads to scope the subsequent SSH(N) investigations. The selected scenarios break down into two defensive scenarios and an offensive one. It was considered that by simulating these three scenarios, USGOT could reveal a measure of effectiveness (MOE) for UUV payloads, which in turn could be used to inform the resultant designs for of SSH(N) concepts, including the overall performance of the SSH(N).

3.5.2 SCENARIO 1: SEA DENIAL IN LITTORAL AREAS (DEFENSIVE MISSION)

A typical sea denial scenario could involve deploying the UUV clusters far away from the SSH(N) in littoral areas (United States Navy, 2004). This would require UUVs to be deployed in several local regions, but not a requirement for 360-degree coverage of the sea around the SSH(N). The UUV network would be set up for the detection and possible prosecution of enemy ships at a standoff distance from the SSH(N) – thus reducing the risk of detection to and engagement by the submarine. To guarantee the localised capability, the UUVs would form a closely-knit net for each individual cluster, where the separation of Category B and Category C UUVs would be limited (to around 25 nautical miles from each other). To ensure the SSH(N) is as far down threat as possible, the Category A UUVs would be placed as far from the SSH(N) as operationally possible (typically 50-75[1] nautical miles, as suggested by the United States Navy (2004) UUV Master Plan 2004).

The UUV net created using USGOT was intended to be capable of detecting enemy vessels with an extremely high probability (>99%[2]). The clandestine nature of a UUV network means that it should be possible to project the threat of a UUV network occupying any one of a number of adjacent regions – even if UUVs are not actually deployed. If the objective of deploying the SSH(N) would be to deter enemy use of the sea, then the capability of the SSH(N) could be considered to be enhanced.

3.5.3 SCENARIO 2: TACTICAL STRIKE AGAINST ENEMY COASTAL DEFENCES (OFFENSIVE MISSION)

A tactical operation to destroy an enemy's coastal defences in preparation for amphibious assault could conceivably be achieved by a single SSH(N). Beforehand, the UUVs onboard an SSH(N) could be used to

[1] It is acknowledged that it is possible future UUV CONOPs may call for stand-off distances of 100-200 nm to increase closing time by an opposition vessel to a length deemed by more acceptable.

[2] There are several unquantifiable factors such as topological and oceanographic interference, which might make a 99% detection probability unachievable. However, in the absence of any accessible data, the detection model used in USGOT assumes such a high detection probability.

provide ISR and detailed oceanographic information back to the command centre. Land, surface and subsea defences could be identified and categorised. The UUVs might then be able to seek to remove subsea threats to both the SSH(N) and the likely amphibious forces by conducting Mine Countermeasure (MCM) operations, as well as track and trailing enemy vessels. ISR could be enhanced by the deployment of Category C “fire and forget” type sensor UUVs and communication buoys. Forward deployed sonobuoys might also be used to provide an early warning system against threats from opposing submarines.

An array of sensors could provide Electromagnetic Intelligence (EMINT) and Signal Intelligence (SIGINT) on any coastal defensives systems of both a static and mobile nature. The identification of these systems allows for their elimination by a third party strike or from land attack missiles launched from the SSH(N) should they also be part of its payload. The SSH(N) could also act as a forward operating base for Special Forces (SF) deployment, potentially utilising large (approximately 10,000 kg) MUVs and possibly augmented UUVs providing close-in fire support for time-critical strikes.

The UUV network could also provide a defensive shield around the SSH(N) or create a “hold at risk” setup on an enemy port (United States Navy, 2004) – thus deterring enemy reinforcements from leaving their home port. The clandestine nature of a UUV network means that it might be possible to project the threat of a UUV network blockading a port. To ensure the SSH(N) is as far away from the threat as possible, the Category A UUVs would need to be placed a significant distance (typically 50-100 nm) from the SSH(N).

3.5.4 SCENARIO 3: CAPITAL ASSET PROTECTION (MARITIME SHIELD/PROTECTED PASSAGE) (DEFENSIVE MISSION)

A capital asset, such as an aircraft carrier, needs to be protected from threats of different origins while in theatre. For traditional Anti-Submarine Warfare (ASW) / Anti-Surface Warfare (ASuW) threats from manned ships and submarines, the deployed UUV net could provide an increased detection area, especially in the subsea environment. This would allow threats to be tracked and reported to a command centre. Threats, such as an opposition combatant vessel, could be clandestinely trailed, increasing the chances of a successful prosecution from carrier group vessels that are capable of engaging such threats.

Additionally, UUVs, which should have low signatures and thus be hard to detect, could be utilised to prosecute the source of the threat directly. As the network of UUVs would be intended to be at a significant distance (tens of nautical miles) away from the capital asset, this would provide the ability to intercept fast moving attacking vessels and detect incoming torpedoes.

ASW against UUVs might require the deployment of additional sensors (linked either to the SSHN or to a third party command centre) to detect enemy UUVs that could potentially attack the capital asset from depths that traditional submarines cannot achieve due to UUVs not necessarily requiring a pressure hull. The enhanced detection capability from a deployed UUV network could also increase the probability of short-range detection of enemy UUVs with very low signatures.

The UUVs would form a closely knitted net, with the separation of Category B and C UUVs being limited to (say) five nautical miles. Category A UUVs could be placed in the vicinity of the capital asset. This should ensure an adequate number of links between UUVs in the entire deployed net. To reiterate, the three scenarios are only meant to be conceivable and not based on actual CONOPs. For instance, a fast carrier group wanting to escape detection may actually require a reduced area covered by deployed UUVs and shorter UUV transit times if operating in deep water.

3.6 RESULTS FROM THREE EXAMPLE SCENARIOS USING USGOT

3.6.1 INTRODUCTION

Only those results from one scenario (Scenario 1) are detailed due to the similarity they have with the results from the other scenarios. The full results of all three simulations are presented in Appendix C. Preliminary simulations indicated that due to the dominance in the overall displacement demands on the SSH(N) by Category A UUVs, as well as their operational importance of being cluster ‘hubs’, the simulations for each scenario suggested a likely number of Category B and C UUVs, with just Category A UUV numbers differing between scenarios. From the preliminary USGOT simulations, it was found that 30 Category B and 30 Category C UUVs were effective and stable numbers to adopt for all three scenarios.

It was assumed in the USGOT simulations that for each Category A UUV, it would be the ‘hub’ of a UUV cluster with approximately 5-12 UUVs Category B and C UUVs in each cluster. The individual displacements of the UUVs used were kept constant in all the simulations to compare results fairly, and Table 8 outlines the UUVs used in the USGOT simulations.

Table 8 – Composition of UUVs Simulated in USGOT Investigations

UUV Category	Number	Individual Weight [kg]	Total Weight [Tonnes]
A – Large UUV/MUV	4-12	10,000	40-120
B – Medium UUV	30	850	22.5
C – 'Fire and Forget' Small UUV	30	250	7.5

3.6.2 EXAMPLE RESULT

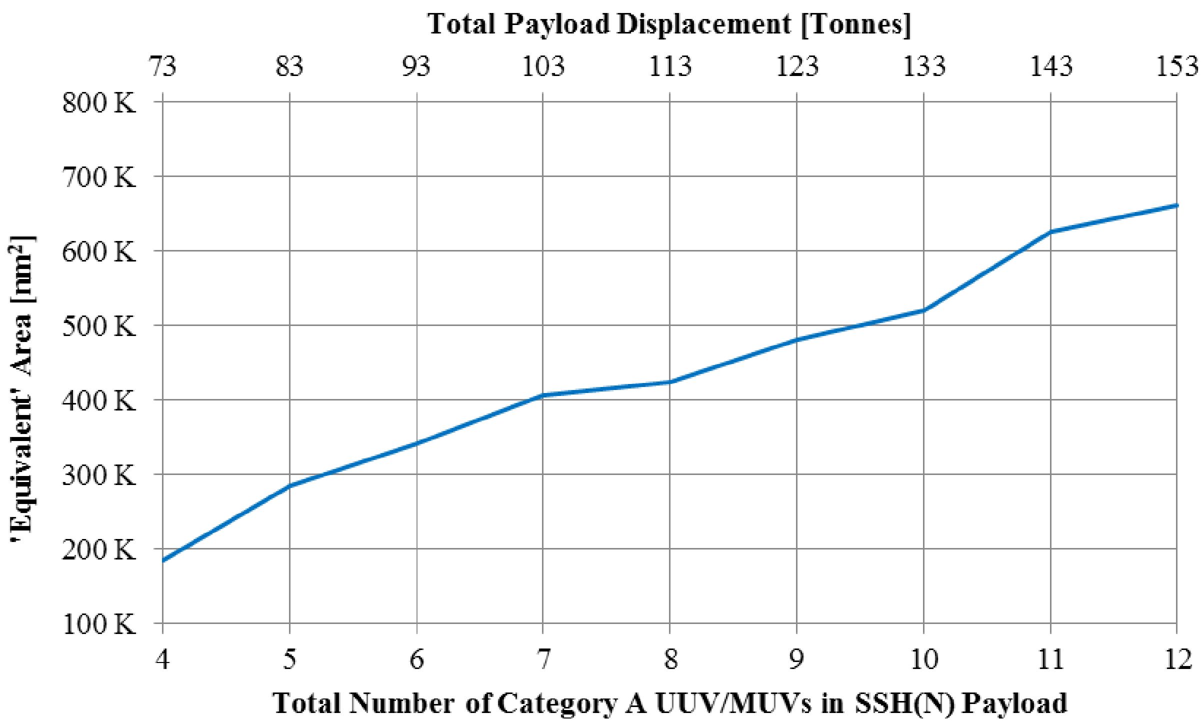

Figure 12 – Scenario 1: USGOT Results (30 Category B and 30 Category C UUVs)

The USGOT simulation results for Scenario 1 are plotted in Figure 12. The results suggest a strong linear relationship between the 'equivalent area' measure of effectiveness defined by Equation 5 (in Subsection 3.4.3) versus the number of Category A UUV/MUVs. This trend indicates the dominance of Category A UUV/MUVs in the effectiveness of UUV payloads because they drive the global distances from the SSH(N) of the clusters of UUVs, which was seen to be the primary driver in maximising the 'equivalent' area score (as well as the area covered by the UUV net). The slight zigzagging pattern in Figure 12 indicates that there are preferable numbers of Category A UUVs (as illustrated by the ‘steps’ in the result from the Payload Calculator equation results shown in Figure 9 on page 71). The zigzag is caused by two sequential numbers of Category A UUV producing the same number of UUVs on-station; however with differing feasible transit distances. There are differences in ‘equivalent area’. For example, according to the results, seven or eight Category A UUVs produce similarly effective UUV payloads due to both being able to support four UUV clusters on-station. However, every additional Category A UUV increases the direct payload demand on the SSH(N) by some 10 tonnes (and impact on the SSH(N) itself as well; in this research an extra 30% to 50% of payload displacement has been assumed, depending on LARS and stowage configurations).

If the SSH(N) has only a very small number of Category A UUVs (<4), these results predict the Radius of Operation (ROO) of the UUV fleet would be limited to fielding a single UUV cluster on-station. This could endanger the SSH(N) by forcing closer to the threat and increasing the risk of the SSH(N) being detected by enemy vessels. For this reason, according to the USGOT simulations, to perform the scenarios suggested in Table 7, a minimum of four Category A UUV/MUVs are required in a UUV payload to form a ‘safe’ minimum of two clusters.

3.7 CONCLUSIONS FROM THE USGOT INVESTIGATIONS

3.7.1 ANALYSING THE RESULTS

The results from the preliminary simulations using USGOT highlighted that a sensible number of Category C UUVs would have very little effect on the ‘equivalent’ area score and thus the effectiveness of a UUV fleet in the three representative scenarios presented. This was due to the Category C UUVs’ small volume precluding them from having an extensive radius of operations (around ten nautical miles) from their source of energy. Category C UUVs are considered disposable and so the performance level of a given UUV net cannot be considered persistent. Both the availability and operational effectiveness of Category C UUVs would be expected to deteriorate over time. It is considered likely that the Loss Ratio (LR) for deployed Category C UUVs, whether just deployed or deployed and launched, would approach 100% and the total number of hosted Category C UUVs would be higher than the 30 assumed in this chapter’s simulations, should multiple missions be addressed using USGOT.

The greater volume of the Category B UUVs means they have a sufficient radius of operation (typically around 50 nautical miles) to have a local effect on the cluster net and hence on the overall UUV net’s score. However, where the Category B UUVs are not directly linked operationally to other UUVs from other clusters, their influence on the UUV net was seen to be limited, as they only increase the 'equivalent area' score at a localised (cluster) level.

As the Category A UUVs have been assumed to always be linked to the other clusters, as well as to the SSH(N), they form the backbone of the net and thus become the major driver in the coverage a UUV net can provide. It is this, coupled with the assumed superior operating radius (typically, about five times that of the Category B UUVs), which makes the number of Category A UUVs the dominant variable in the UUV fleet. In the preliminary simulations, the assumed individual displacement of the Category A UUVs was found to have a limited effect on the coverage area of the UUV net, depending on the operational constraints imposed by the scenario simulated in USGOT. Category A UUVs had greater possible ROOs than Category B and C UUVs and were assumed to be able to detect vessels from longer range. The USGOT results indicated that the number of Category A UUVs had a greater influence than increasing their individual displacement. Clearly, the size and number of the Category A UUVs would have a significant effect on the total UUV payload size to be hosted by an SSH(N).

The USGOT preliminary simulations for all three scenarios have shown that for a small change (e.g. a few additional UUVs) in the total numbers of Category B UUVs, there is no effect on the 'equivalent area' score. This is due to the Payload Calculator in USGOT showing that increasing their number was insufficient to affect the performance of the on-station clusters. Each cluster was made homogeneous in terms of both number and composition of UUVs to save computation. This explains why a significant number of additional (typically five to seven) Category B and Category C UUVs were seen to be required during the preliminary simulations in USGOT (for any of the three scenarios) to make any difference in the UUV net's 'equivalent' area score.

3.7.2 USGOT IMPLICATIONS FOR AN SSH(N) WITH A SIGNIFICANTLY LARGE UUV PAYLOAD

The differing impact of each UUV category on the total UUV payload's capability led to focussing on how many Category A UUVs would be required when undertaking the initial submarine sizing in the design procedure. Thus, during the generation of an SSH(N) concept, the designer's focus should be on the number and size of Category A UUVs – as these would significantly affect the rest of an SSH(N) design. The USGOT scenario from which to obtain the UUV payload's effectiveness would also need to be selected. In subsequent stages of design, ‘fine tuning’ of the UUV payload’s performance could occur by investigating more closely both the Category B and then Category C UUV numbers.

According to the USGOT simulations, a significant number of Category A UUVs (more than three) would have implications on the size of the SSH(N), with each extra UUV (plus LARS and stowage considerations) adding some fifteen tonnes to the payload impact. The results from the USGOT simulations indicated that a minimum of four Category A UUVs has to be included in a UUV payload for an SSH(N). The corollary is that USGOT has predicted that to perform the three scenarios simulated, which have been considered to be among the most taxing proposed UUV missions, a UUV payload displacement of at least 90 tonnes (including LARS and stowage) would be required. The UUV payload was considered significantly large because it would be an order of magnitude larger than UUV payloads likely to be accommodated in current submarines (likely SSN). These submarines are orthodox in the style of design, with their conventional weapons payload just augmented to host a few Category B type of UUV. An example of such a submarine would be Saab’s (2015) Swedish A26 SSK design. It was concluded that significantly larger UUV payloads would be consistent with an SSH(N) concept and lead to submarines with unorthodox styles of design. This is turn would justify the proposed ‘generic’ submarine design tool as it would need to be able to generate concept designs with notably differing styles of design. Furthermore, this justifies the requirement to explore the unrefined solution space as an initial step to concept exploration. The novelty of an SSH(N) carrying a substantial UUV payload means that the preferred style(s) would not be readily predicted using existing designs as a basis.

The large UUV payloads suggest that SSH(N)s would require a large displacement (>5,000 tonnes) to host such a UUV payload. The total weight of a significantly large UUV payload, accompanied by LARS and stowage was predicted to be of the order of 150-200 tonnes. The UUV payload would likely be incorporated into a submarine’s design along with the ‘traditional’ payload items such as heavyweight torpedoes (HWTs) and sonars – driving up the SSH(N)’s displacement. It is conceivable that the CONOPs for an SSH(N) would allow for a reduced ‘traditional’ payload, such as fewer HWTs limited to the purpose of self-defence. For comparison, Burcher & Rydill (1994) noted that the payload of a typical SSN is 8%[1] – so a 5,000-tonne boat could conceivably have 400 tonnes of total payload. The likely displacement of the submarine suggests that nuclear-powered propulsion would be preferable – as a large boat requires high levels of power (typically multiple megawatts) to propel it through the water. Some non-nuclear submarines with a displacement greater than 3,000-4,000 tonnes have recently been constructed – for example, Japan's 4,200 tonne *Sōryū*-class (Naval Technology, 2015b). Although such large non-nuclear boats are unusual, it is nevertheless conceivable that a 'Mothership' submarine could be non-nuclear powered if it had a similar displacement. However, if an SSH(N) required the larger displacement of a modern SSN, such as the RN's *Astute*-class (Naval-Technology.com, 2014c) which has a displacement of some 7,500 tonnes, it would almost certainly require a nuclear reactor.

3.8 CONCLUSION

This chapter has explained the construction of the OA tool, USGOT, and the scenarios used to simulate the deployment of a fleet of mixed UUVs. The simulations have indicated that for UUV missions that have been considered to be among the most taxing, the number of Category A UUVs were the primary driver for the effectiveness of a UUV payload to undertake a mission. The reason for modelling UUV operations is not to create an attractive modelling approach, but instead is restricted to providing insight into new submarine concept design. This is in accordance with the reliability limit of modelling at a concept level of granularity, which has been discussed by Andrews (2013).

It was concluded that significantly large (around 60 tonnes or more) UUV payloads needs to be assumed to be hosted by SSH(N)s as input to the proposed 'generic' submarine design tool. The large payload weight is driven by the requirement to have at least a few large Category A UUVs within the hosted UUV payload. The large UUV payloads suggested by USGOT analysis infer that SSH(N)s powered by nuclear reactors would be advantageous, due to the likely whole boat displacement (>3,500 tonnes) required to host such a UUV fleet.

[1] This assumes that the weight breakdown provided by Burcher and Rydill is applicable to SSH(N)s. It was recognised that Burcher and Rydill based their weight breakdown on pre-1994 submarines (i.e. one or two generations behind current day submarines and smaller at some 3,500 tonnes). However, it was postulated an acceptable level of the proportion submarine dedicated to payload has not radically changed in the intervening years – suggesting applicability. It should be noted that while 3,500 tonnes displacement represented a large submarine in 1994, 5,000-8,000 tonnes is now typical for a modern SSN, and possibly, by 2030 typical SSN displacements could be greater still. Furthermore, the proportion of displacement assigned to propulsion and accommodation is a rising trend, so the 8% devoted to payload may fall in the future.

SSH(N)s with such large UUV payloads have been considered likely to entail unorthodox and novel styles of design – unlike the current existing design practice of augmenting orthodox designs with a few torpedo size UUVs. This was considered support to the need for a ‘generic’ submarine design tool.

CHAPTER 4 - THE CONSTRUCTION OF SUPERB

4.1 INTRODUCTION

This chapter outlines the basis of the ‘generic’ submarine design tool proposed in Subsection 2.7.1. The tool has been designated Submarine Preliminary Exploration of Requirements by Blocks (SUPERB). Particular attention has been paid to the novel internal arrangement method: ‘Compartment X-Listing’, which was seen to be necessary for the reasons spelt out in Section 2.5. The purpose of this chapter is to describe both SUPERB and its components. Chapter 5 contains the validation of SUPERB.

Following a top-level description of SUPERB and its context, the chapter describes the three sequential top-level stages constituting this ‘generic’ submarine design tool, drawing on the Three Stages Model for design by Dym and Levitt (1991):- a) The description of the physical features and equipment that make up the description of a vessel using mathematical models and available data in SUPERB; b) The synthesis of these through an arrangement (which uses a novel arrangement approach in SUPERB); and c) the auditing and analysis of a design, which is seen to be the demonstration of the (concept level) naval architectural balance of a submarine concept design.

4.2 TOP LEVEL EXPLANATION

4.2.1 THE CONTEXT OF SUPERB

A major element of the research was the creation of a tool capable of designing ‘generic’ submarine concepts: SUPERB. This was written in the computer programming language MATLAB. The SUPERB tool is intended to generate submarine concepts (including arrangements) and to assess if they are naval architecturally balanced. SUPERB facilitates the evolution of unrefined potential solutions in the unrefined solution space into the refined solution space. This process is shown in Figure 13.

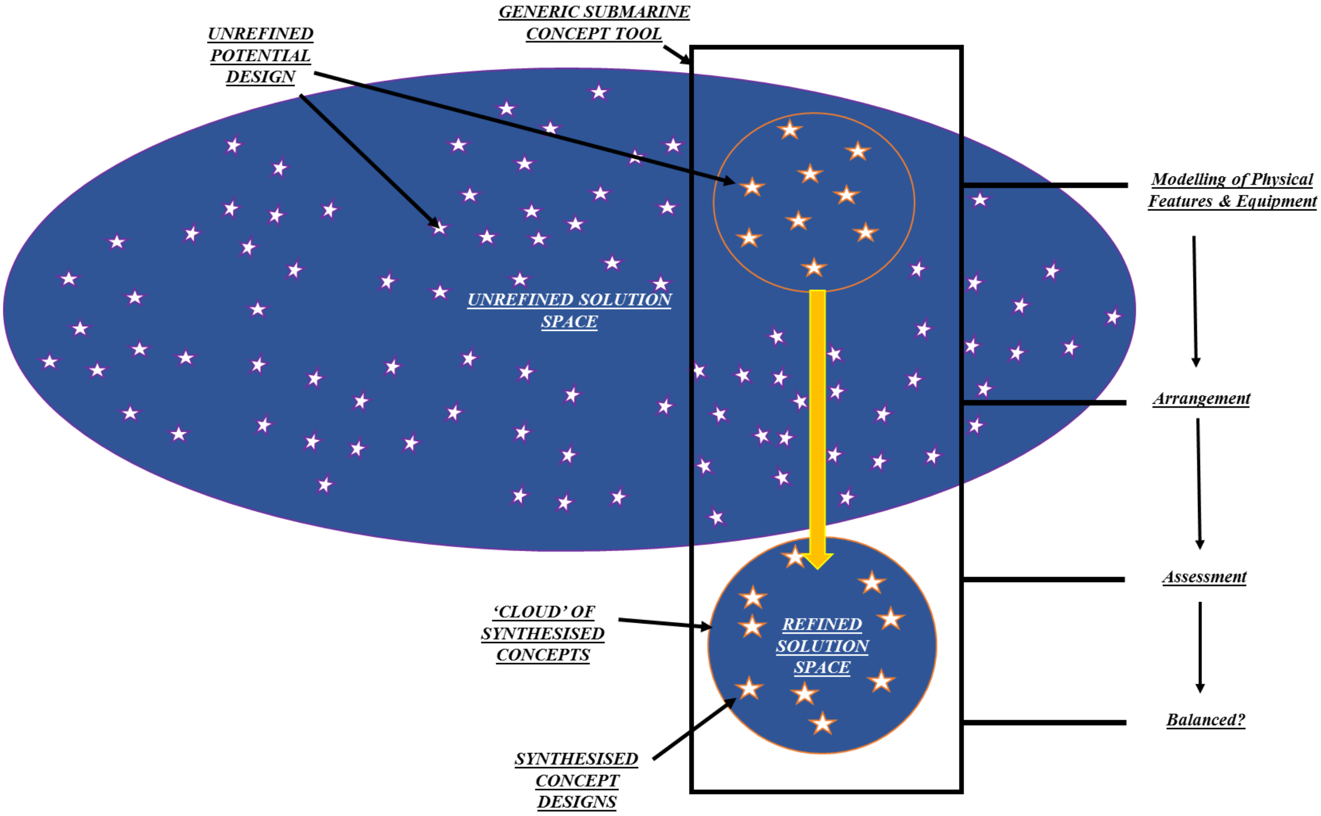

Figure 13 – The Context of SUPERB

SUPERB has been developed as a computer-based tool to meet the objective stated in Subsection 2.7.1 of generating a large number (10^4-10^6) of concept designs in a highly automated manner. The high number of designs was considered sensible to ensure a wide-ranging exploration of the unrefined solution space. The wide-scale exploration was necessary, as no established designs were discovered in the State of the Art review (Section 2.2). Another objective identified in Subsection 2.7.1 was that using SUPERB enabled 'generic' submarine concepts to be designed. This then ensured that significantly different concept designs, including potentially 'unorthodox' designs, could be considered as part of concept exploration, following a wide-ranging exploration of the unrefined solution space.

4.2.2 SCHEMATIC OF SUPERB

SUPERB automates much of the design effort in producing concept designs that can be very time consuming if done 'by hand', such as with the DBB approach, particularly using the GRC QinetiQ's (2015) Paramarine preliminary ship design toolset. SUPERB is intended to produce concepts, which are essentially generic – this is to minimise direct influence from current design practice when exploring the unrefined solution space.

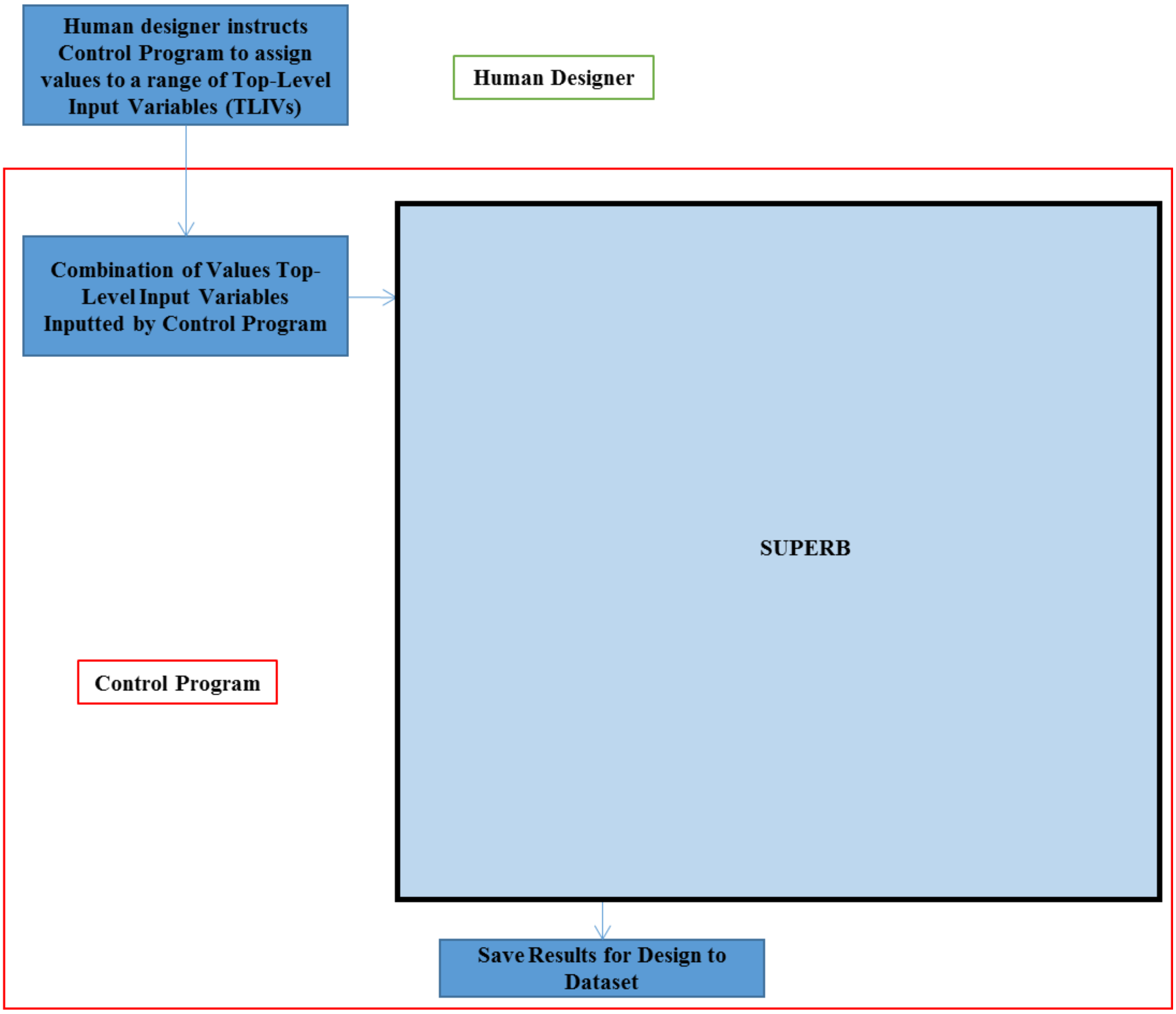

Figure 14 – SUPERB's Control Program's Interactions

Figure 14 shows SUPERB (defined by the black boundary) and its interaction with a control program. The control program is responsible for instructing SUPERB to generate specific submarine concept design solutions in order to populate the unrefined solution space. The (human) designer (outside the red box) decides on the range of values for each top-level input variable, such as submerged displacement between 5,000 and 10,000 tonnes; or whether Category A UUV stowage is either internal or external to the pressure hull. These ranges effectively limit the extent to which unrefined solution space will be explored. The control program picks different combinations of top-level input variable values[1] to produce a range of submarine concept designs

[1] See Table D1 in Appendix D Section D.2 for a typical set of values used

using SUPERB, of which a portion will subsequently be found to be naval architecturally balanced. The control program is also responsible for collecting the results from the population in the unrefined solution space.

SUPERB is based on Burcher and Rydill's (1994) approach to submarine design (reproduced in Figure D1 of Appendix D[1] Section D.1) but also takes account of the likely UUV payload demands arising from the demand suggested by USGOT and decisions made by the designer regarding a prospective submarine's associated performance features and style of design. SUPERB receives this information to generate (mostly) generic submarine concepts. The schematic of SUPERB for creating an SSH(N) concept design is summarised in Figure 15.

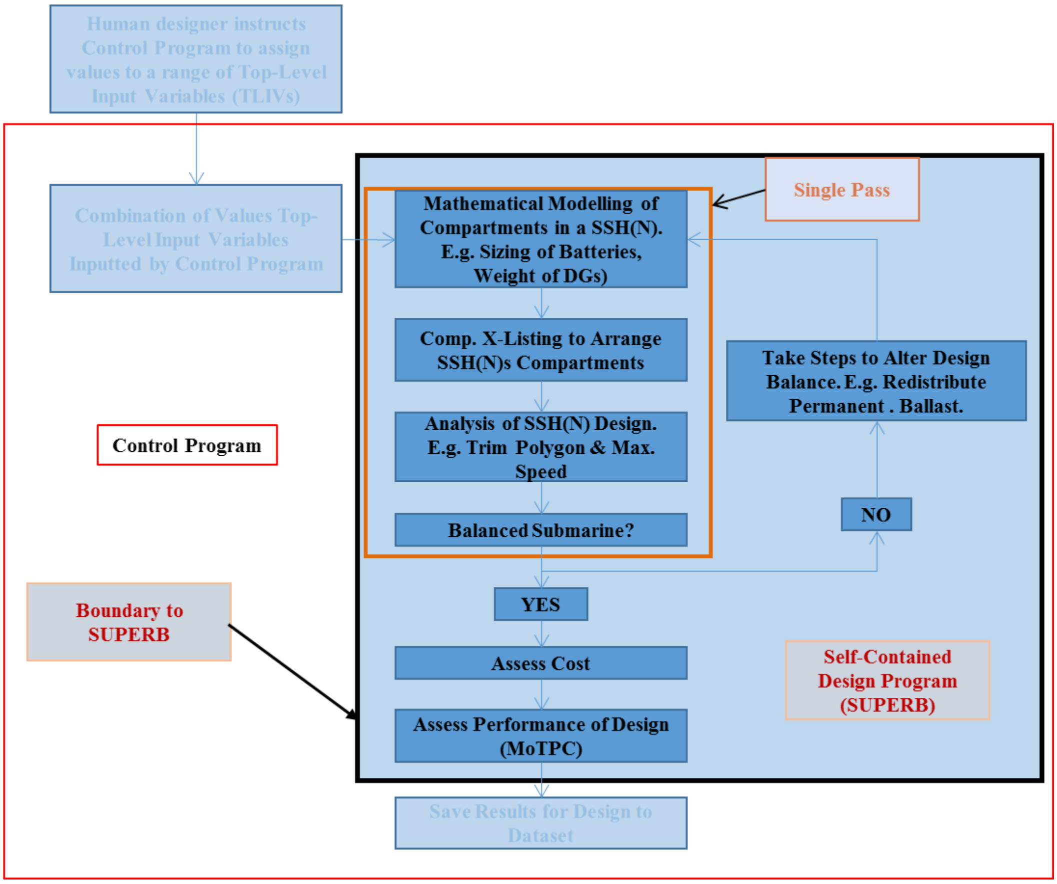

Figure 15 – Schematic of Submarine Preliminary Exploration of Requirements by Blocks (SUPERB) for Creating a Submarine Design Option

[1] Appendix D presents further notes on SUPERB. These include schematics on the structure of its code and information on how it handles data (such as that related to compartments). Appendix D also contains schemes SUPERB adopts for assessing cost and design margins. It also contains information it accesses to produce the refined solution space.

In Figure 15, the orange box shows the part of SUPERB that performs a single pass of the design process to produce a submarine design. The first component in this box generates the submarine's compartments (and physical features and major equipment items) to model a design at a concept level of definition. The subsequent components (second and third boxes in the orange box) generate an arrangement and then assess it for its naval architecture balance in weight, buoyancy, trim, transversal and longitudinal stability and powering. Following the single pass, SUPERB employs a sequence of steps that are intended for the design to achieve naval architectural balance (right-hand box). However, not all designs produced will be balanced by performing these actions. These balancing steps are sequenced in terms of their perceived impact on the overall design. This is intended to replicate <u>some</u> (relatively basic) actions a naval architect would take to balance concept design of a submarine. The steps taken are not intended to alter the design's style, and hence, will not significantly change the relative compartment positions in a design's arrangement. The processes of these steps have been outlined in Appendix D Section D.7.

SUPERB is also intended to 'recognise' if further design iterations will not produce any improvements to the naval architectural balance of a submarine design. For some unbalanceable designs, SUPERB will indicate that the proposed SSH(N) design option has zero performance, and so that option would be ignored during the production of the refined solution space. Thus, such design options are considered to be outside the 'clouds of concepts' in the unrefined solution space shown in Figure 13 on page 86.

If a design is found by SUPERB to be adequately naval architecturally balanced, it is passed outside the single-pass loop (orange box in Figure 15) to SUPERB's costing module, so that its unit production cost (UPC) can be calculated (see Section 1.1). The UPC has been adopted because:- a) it was readily available from the Submarine Design Course; and b) it was considered unnecessary in this demonstration to devise a conceivable cost metric which considered the Through Life Costs (TLC) of a novel submarine. Finally, a measure of performance for the design is predicted using the MoTPC scheme devised for SUPERB, which is explained in Section 6.2 and detailed in Appendix E. It is also discussed in Chapter 8 as it is an important issue concerning the determination of "attractive" designs.

4.3 MATHEMATICAL MODELLING

4.3.1 REASONS FOR MATHEMATICAL MODELLING OF COMPARTMENTS AND EQUIPMENT

In Chapter 2, it was concluded that mathematically modelling of the arrangement of a submarine's compartments and equipment to meet the submarine's functional needs is a vital process to creating a 'generic' submarine design tool, as those components are a pre-requisite in the generation of a concept's architecture and achieving a balanced. Relevant data and knowledge for these mathematical models were discussed in the State of the Art review in Subsections 2.4.3 and 2.4.4. Appropriate data has been largely drawn from the UCL Submarine Data Book (NAME Office, University College London, 2012b), as well as from open sources, such as commercial product catalogues. Some of the key mathematical models are described in Appendix F Sections F.2 to F.8. In addition, assumptions made concerning these models are listed in Table F1 in Appendix F Section F.9.

4.3.2 THE MATHEMATICAL MODELLING MODULE OF SUPERB

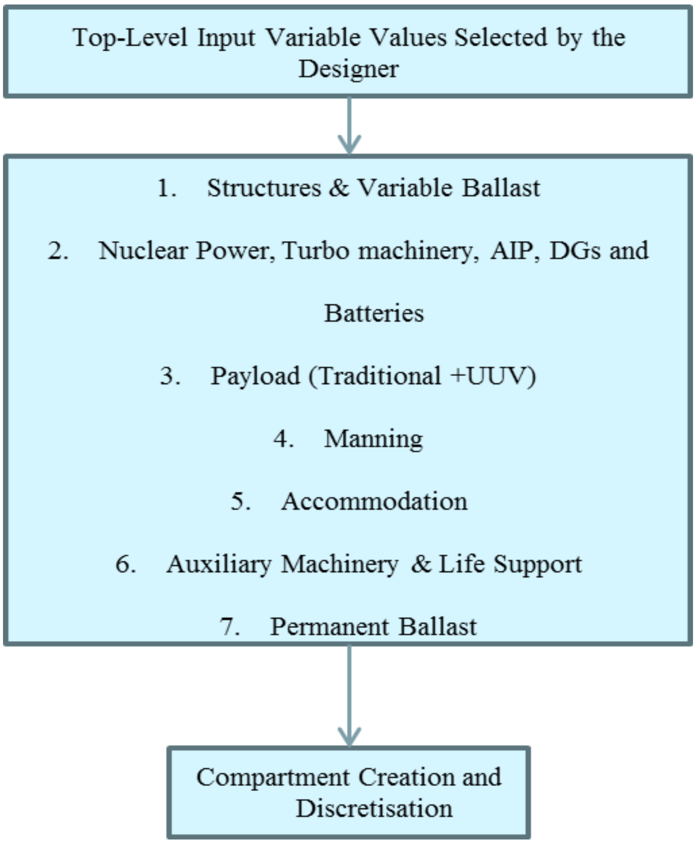

Figure 16 – Mathematical Modelling Module of SUPERB

The orange box of Figure 15 has four sequential steps to execute a single pass of the design process. Firstly, all the main compartments and major equipment items that make up a submarine at the early stages of design are described using a set of mathematical expression. These mathematical models have been developed using a combination of physical laws, past design practices and expert-based ‘rules of thumb’.

The Mathematical Modelling Module of SUPERB (first box inside the orange box of Figure 15) is summarised in Figure 16. The top-level input variables, such as submerged displacement and top speed, are inputted by the designer into the modelling section, then the compartments and equipment are described mathematically in the order shown, drawing on the built-in database. Finally, the compartments (containing the relevant equipment) and the structures in which they are located are discretised into cubic voxels (to address arrangement in the next section of SUPERB). An explanation of voxels and a convergence study into voxel dimensions has been included in Appendix D Section D.8.

4.4 GEOMETRIC ARRANGEMENT

4.4.1 CONFIRMING THE NEED TO PERFORM ARRANGEMENT IN SUPERB

The analytical method[1] described by Kormilitsin and Khalizev (2001) was initially adopted in setting up SUPERB but was found to be inappropriate. The rationale behind using Kormilitsin and Khalizev’s analytical method was that using Excel enables a rapid generation of the major physical features and equipment for an SSH(N), without the complex (and hence time-consuming) process of generating an accompanying arrangement. However, it proved too blunt a tool for creating and assessing submarine designs with sufficient accuracy. The simple summation of geometric characteristics of compartments within the pressure hull was found to be insufficient to determine if the selected pressure hull configuration was of sufficient size to meet all geometric demands. The arrangement constraints of particular compartments, such as the torpedo stowage compartment, which needs to be placed adjacent to the torpedo launching equipment, could not be ensured using the analytical method. Furthermore, analytical modelling was unable to take account of overall arrangement constraints, such as the need to fit all of a relevant set of compartments on a specific deck in a

[1] The analytical method is the simple summation of compartments weights and dimensions, with no architectural layout generated. Instead, generic formulae based on an orthodox style of design are used to predict if a design has naval architectural balance.

practical manner (usually in a longitudinal sequence). Thus, it proved impossible with the Excel-based analytical method to assess if an SSH(N) arrangement was practical or even feasible.

It was concluded that the architectural arrangement of the compartments had to be defined to a reasonable level to ensure generation of feasible submarine arrangements (i.e. naval architecturally balanced to a concept level). Thus, it followed that SUPERB should have the capability to generate arrangements – confirming one of the objectives spelt out in Subsection 2.7.1.

4.4.2 THE SEMI-AUTOMATED DEVISED ARRANGEMENT METHOD

To meet another stated objective in Subsection 2.7.1, SUPERB should be sufficiently well automated to allow the generation of a large number of early concept designs to populate the unrefined solution space with a large number of potential design in a practical timeframe. A major feature necessary to ensure such submarine design concepts are subsequently (sensibly) balanced is a sufficiently 'worked-up' arrangement. It was considered that producing a concept level arrangement should be largely automated in order to reduce the generation time. However, the arrangement method devised is not *fully* automatic, as some designer originated decisions need to be made upstream in SUPERB's procedure, such as designating which compartments are tankage and thus likely to be placed on the tankage deck. It was considered that the arrangement method – taken as a whole – could be said to be an essentially automatic one. The location of compartments is performed by the (fully) automated arrangement process, which is downstream from the designer's decisions and is part of the arrangement method. The arrangement process consists of two steps: the formatting compartments and then locating compartments.

For the 'automated' arrangement method to be performed, it was considered that the devised arrangement process had to able to handle any conceivable compartments with the proviso every compartment has been correctly formatted in SUPERB's own format specific to its arrangement process, which is described in Appendix D Section D.9. This ensured that the arrangement process was flexible and could thus handle a range of submarine concept designs – including unorthodox ones. It was also considered that the devised arrangement process had to be able to arrange compartments depending on some general characteristics, such as the height and density of a compartment.

SUPERB's arrangement process features an algorithm to locate compartments called the packing algorithm. This algorithm has a similar purpose to the Space Allocation Routine in the Packing Approach (PA) developed by van Oers et al. (2009). The goal of the packing algorithm is to pack the compartments into a vessel in a geometrically valid and efficient (i.e. dense) manner. The packing algorithm (and the Delft Space Allocation Routine) is controlled by a set of rules that have been designated "packing rules". Packing rules have been described by Duchateau et al. (2015). The packing algorithm used by the arrangement process in SUPERB is considered largely generic, as each compartment to be arranged must have a set of characteristics defined in a pre-defined format to be handled by the algorithm.

The number and type of packing rules used by van Oer's PA have been explored before in approaches to generating concept arrangements for ships, and the conclusions of this exploration have been described by Duchateau et al. (2015). Duchateau et al. have remarked that currently packing rules should be manually specified *a priori*.

However, Zandstra (2014) investigated generic "dynamic" packing rules, which adapt depending on the systems the designer has selected to comprise a design. The dynamic packing rules put forward by Zandstra did not consider the performance of synthesised whole ships or dynamically adapting packing rules during packing. Zandstra's dynamic packing rules were intended only to increase the likelihood of achieving a geometrically valid packing of compartments. Nevertheless, it was concluded from Zandstra's investigation that packing rules could be adapted dynamically, depending on a set of inputs.

If novel physical features are to be considered, then this could be a limitation as the packing rules may be limited by not being able to be specified *a priori*. Thus for SUPERB, it was concluded that an arrangement process driven by novel generic dynamic packing rules was needed, to incorporate feasible arrangements and generate novel physical features. This was considered achievable following on from the work of Zandstra (2014). An approach has been developed so that SUPERB can address this novel layout generating process and is called "Compartment X-Listing" (see the next section).

4.5 OUTLINE OF THE BASIS OF THE COMPARTMENT X-LISTING FEATURE

4.5.1 INTRODUCTION TO COMPARTMENT X-LISTING

The location of compartments within a submarine design's pressure hull is governed by the Compartment X-Listing approach used by SUPERB, which is outlined in Figure 17 on page 94. The following description pays particular attention to the sequence in which the compartments are arranged.

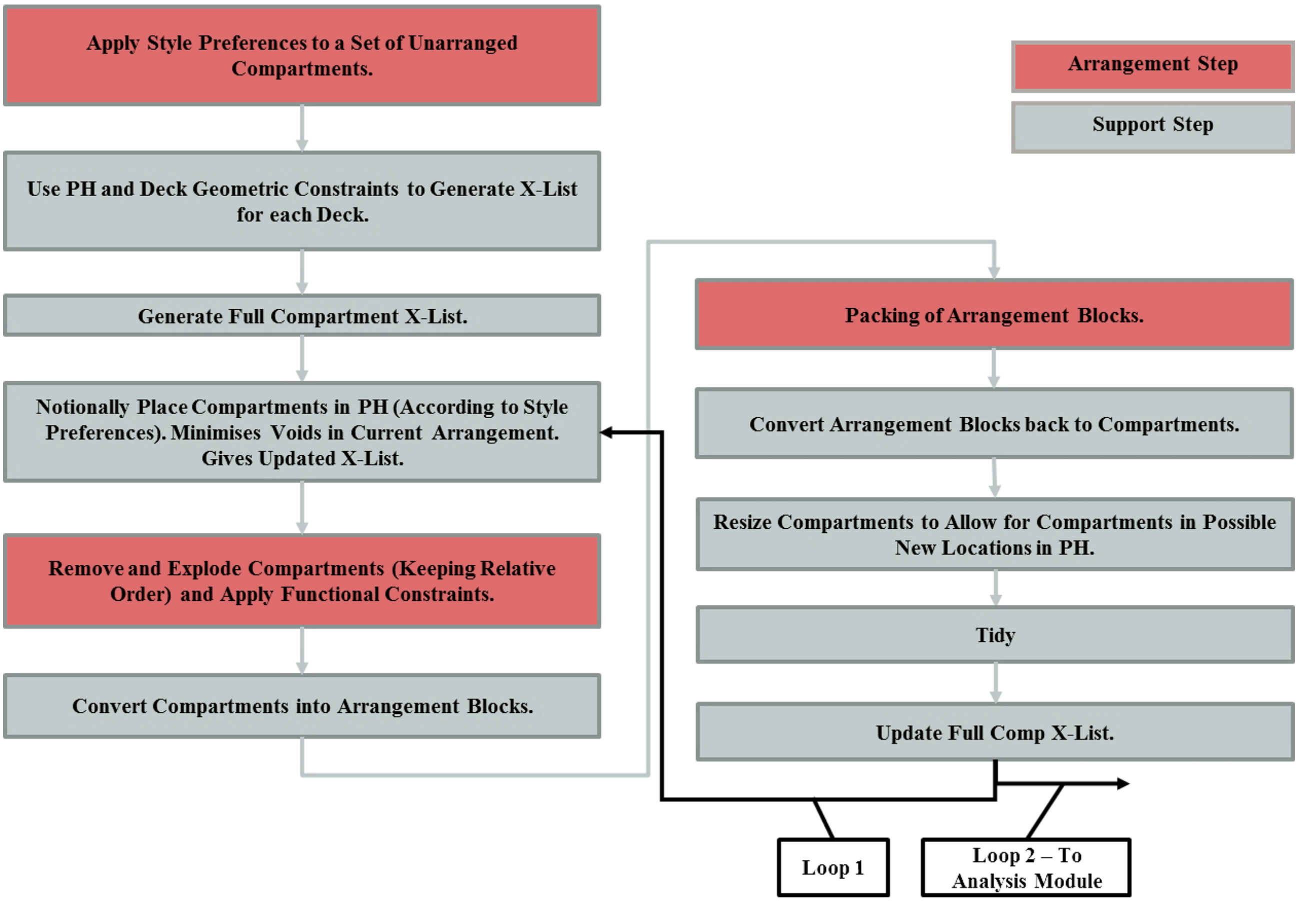

Figure 17 – The Schematic of Compartment X-Listing Arrangement Approach

The approach adopted in designing the Compartment X-Listing feature of SUPERB was that it should generate a sequence that would arrange compartments inside the pressure hull. 'X' denotes the direction in which the compartments would be placed in the pressure hull(s), longitudinally; from aft to forward. This is similar to the approach adopted ordering the sequence of 'dropping' blocks in the computer game 'Tetris' (Gerasimov, 2014). The approach is illustrated in Figure 17 and has three main steps (red boxes), called the Arrangement Steps, each of which significantly modifies a putative arrangement. The other intermediate grey boxes (called Support Steps) are steps in the approach that addresses the generation, management or alteration of the X-List, together with possible minor alterations to compartment geometry. The first two Arrangement Steps deal with the generation of an X-List, which is considered able to produce a potentially naval architecturally balanced design once the arrangement process is completed, while obeying applied arrangement constraints. The third Arrangement Step deals with the packing of the compartments into the initially defined pressure hull (i.e. it can change due to later SUPERB processes) to create the arrangement using the packing algorithm.

The arrangement approach is performed in two loops. This is because the compartments have been located to the 'correct' decks after the first loop, as opposed to the decks implied before the packing Arrangement Step. Following this 'correct' location, the geometry of a compartment can be refined to meet its geometric requirements. This is done in the Resize Compartments Support Step, which is the anti-penultimate step in Figure 17. After the second loop the overestimation of the volumetric demand placed by the internal arrangement of the space provided by the pressure hull ought to reduce. It was seen through preliminary observations of the arrangement approach that the arrangements produced after the first and second loops were similar. The discrepancies were rooted in some compartments' geometries changing slightly.

4.5.2 THE FIRST ARRANGEMENT STEP: STYLE PREFERENCES

The term Style, which has been explained in Subsection 2.4.2, was originally adopted to address emergent whole ship properties, some of which are not readily quantifiable. "Style Preferences" have been proposed in this research to address design issues which may not be readily quantifiable in an effort to produce designs considered stylistically attractive (as determined by some metrics devised for use by the Style Preferences). The Style Preference metrics are indicative given they are unquantifiable. They are indicative only to inform decision-making and not be used be used to quantify any design trade-off. An example of using a Style Preference could be one intended to ensure better ergonomic movement of personnel onboard a submarine. Style Preferences could influence a 'good' style and performance of a design. For example, a deliberate style choice would be ensuring that a design has a sufficient margin to accommodate growth in the vertical position of the centre of gravity, likely to be caused by added weight (above the centre of gravity) during the submarine's operational life.

The first Arrangement Step relates to "Style Preferences". There would be many choices to be made within the first Arrangement Step, some of which are outlined in Figure 18. The first sub-step is merely the importing of all the (internal) compartments to arrange them into a single list using the "Bubble Sort" algorithm[1]. The Style Preferences are then applied in the following three sub-steps of Figure 18. If SUPERB was being used to investigate a concept, the designer could select which Style Preferences to impose on an arrangement in the

[1] The "Bubble Sort" Algorithm is a common algorithm used to order lists, typically for ordering from highest to lowest for a set of values. In works by comparing two adjacent values and determining if their positions in a list should be swapped. See sorting-algorithms.com (2008) for a full description.

first Arrangement Step while using SUPERB. The set of Style Preferences shown in Figure 18 for the investigation of SSH(N)s, is not fixed but could be modified by the designer.

SUPERB transfers (internal) compartments from it's Mathematical Modelling Module and places them into a single list.

↓

A "Bubble Sort"[1] Algorithm orders compartments by (descending) density. This is intended to ensure the centre of gravity is sufficiently lower than the centre of buoyancy.

↓

Compartments from the list from Sub-Step 2 are divided evenly (by number of compartments) into a list for each deck, e.g. if there are four decks, No. 1 Deck takes the least dense 25% of compartments and the Tankage Deck takes the 25% most dense.

↓

Apply the "Logistical Effort" (definition provided below in the text) to allow for some human factors considerations to be associated with the arrangement.

Figure 18 – Typical Sub-Steps Currently used in the First Arrangement Step

In the second box of Figure 18, the arrangement of compartments which are likely to provide a design balance, in terms of good transverse stability and margin (BG[1]) is considered. This is followed by ensuring there is a sufficiently low centre of gravity relative to the centre of buoyancy (third box) and longitudinal trim capability (fourth box). Meeting these criteria for an arrangement is a significant part of a design being considered naval architecturally balanced.

In order to impose the Style Preferences, a slightly modified version of the 'logistical effort' metric proposed by van Oers et al. (2009) has been adopted to ensure that personnel movement issues are addressed in the arrangement selection. This 'logistical effort' is calculated using the global (i.e. whole-boat level) positions of compartments and each compartment's function (termed "type" for use in SUPERB). To take account of this 'logistical effort' a mechanical analogy was applied with a 'force' (termed F) between each pair of compartments, whose value is dependent on the compartment type, such as auxiliary machinery and accommodation space. Each compartment is assigned one of ten compartment types (for example,

[1] BG is the distance between the centre of gravity and the buoyancy. It is used to quantify the transverse stability of a submerged submarine.

accommodation and auxiliary machinery). This 'force' between a pair of compartments can be attraction, neutrality or repulsion and its magnitude is proportional to the assigned distance between the pair of compartments (normalised against the boat's length in the longitudinal direction and the boat's height in the vertical direction). This is analogous to solving explicitly in Finite Element Analysis, as described by Zienkiewicz et al. (2005). If 'force' is repulsive, the 'stiffness' (termed by k) between the compartments has a value of -1, for an attractive force that value is 1 and 0 for a neutral force. Thus, for a pair of compartments (numbered i and j) and located at x_i and x_j respectively, the force is:

$$F_{ij}=k_{ij}(x_i-x_j) \qquad \text{[Eqn. 7]}$$

The vector of the 'force' applied to each compartment is $\vec{F}$ and the matrix of the combined compartment combinations for k is called the stiffness matrix (K). $\vec{U}$ is the displacement vector of all compartments. The 'logistical effort' could be minimised (mathematically optimised) by:

$$\vec{F}/K=\vec{U} \qquad \text{[Eqn. 8]}$$

The 'logistical effort' and submerged stability and trim arrangement requirements are traded-off to generate an initial arrangement which is the selected measure of achieving balance. It was recognised that are multiple solutions, all of which could lead to balanced designs. However, since further refinements to the arrangement can be made subsequently, it was considered unlikely that a genuine 'optimum' solution could be revealed (assuming it was possible to agree a basis for 'optimising' the design). Rather, a feasible solution should be sufficient for concept design. All the constraints used in this Arrangement Step are 'soft' constraints. Soft constraints are those with constraint relationships intended to meet a goal (as opposed to an objective) and thus can be violated to an extent decided by the designer. An example of a soft constraint would be placing the Commanding Office's (CO's) accommodation adjacent to the Control Room. In contrast, hard constraints would be ones which must be strictly met under all circumstances. For example, escape towers must be arranged to penetrate the top of the pressure hull to facilitate the emergency escape of personnel.

4.5.3 THE SECOND ARRANGEMENT STEP: FUNCTIONAL CONSTRAINTS

The second step addresses meeting the "Functional Constraints" for individual compartments. These are defined as constraints which can be reduced to the level of explicit definition (hence 'functional'). The Functional Constraints used in this second Arrangement Step can be either hard or soft. The constraints have been used to ensure a feasible submarine is designed. For example, the torpedo stowage compartment is hard constrained to be adjacent to the compartment containing the torpedo tubes. Functional Constraints originate from knowledge sources outlined in Subsection 2.4.4 and it is up to the designer to select which Functional Constraints to impose on an arrangement, when using SUPERB to conduct investigations into novel concepts, such as SSH(N)s. The combined listing of user-selected arrangement constraints from the first two Arrangement Steps has been termed the “Constraint Profile”.

Following the application of each Functional Constraint[1], the X-List is updated automatically as the relative positions (and hence the X-List order) of compartments may have changed. This is important as updating of the list ensures that in the third Arrangement Step (where the arrangement approach places the compartments in their final positions i.e. the equivalent ‘Tetris’ packing is undertaken), the Functional Constraints are obeyed, and the compartments in question are not unacceptably obstructed by other compartments. Obstruction implies a Functional Constraint is not being met by applying the packing algorithm when packing in other compartments. The complexity of generating an arrangement while obeying multiple, potentially conflicting, Functional Constraints means that it is possible for the Functional (soft) Constraints not being met. An arrangement is achieved within Compartment X-Listing by listing the order in which compartments are sequentially (not concurrently) packed. Compartment X-Listing is intended to create an X-List which is ordered so that it ensures that no constraints are being violated. This is illustrated in Figure 19 on page 99. Compartment A is to be longitudinally adjacent to Compartment B, and it should be located immediately after Compartment A, otherwise Compartment C could potentially stop this constraint being met. In Figure 19 this constraint is called Constraint B-A. By applying the soft Functional Constraints to the X-List before the hard ones, it is intended that only the soft Functional Constraints be violated during the packing process because these inform the arrangement but are able to be changed downstream.

[1] Example Functional Constraints are listed later in Table 14 (Sub-Subsection 5.2.2.ii) as part of the validation exercise of SUPERB.

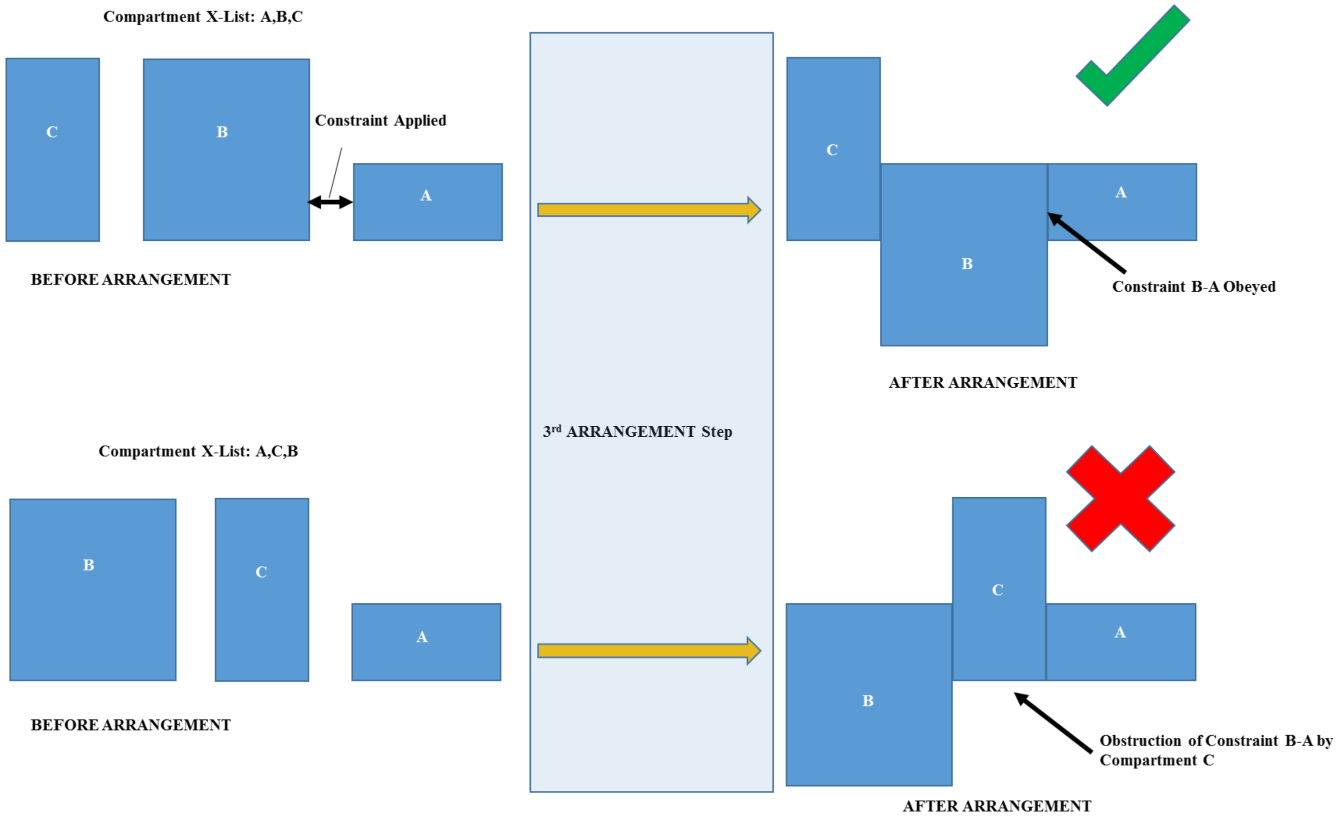

Figure 19 – Compartment X-List Order Sensitivity

4.5.4 THE THIRD ARRANGEMENT STEP: PACKING

4.5.4.i Packing Rules

The third Arrangement Step packs the compartments using the X-List order that emerges from the application of the first two Arrangement Steps. It is the intent of the approach that the compartments are efficiently packed to ensure the arrangement is within the geometric bounds of the pressure hull. The compartments are actually arranged as "Arrangement Blocks". Arrangement Blocks are (cuboid) blocks used to represent the combined geometric and (user-defined) arrangement constraint characteristics of a set of compartments linked by applied arrangement constraints for use in packing. A set of blocks can be used to represent different geometries of linked compartments; for example, two linked compartments that form an 'L' shape can be represented in the third Arrangement Step of the Compartment X-Listing approach by two Arrangement Blocks. Arrangement Blocks allow for the possibility that (in rare cases) multiple compartments have to be treated as a single entity to achieve an acceptable arrangement. Thus, the nuclear reactor and its accompanying access tunnel may need to be arranged simultaneously and hence to ensure this, they are combined into a single Arrangement Block.

However, for simplicity in the current explanation, the arrangement blocks are assumed to be always single compartments and are referred to as such.

The compartments are arranged using a heavily modified algorithm, originally used to minimise the free space in digital images. An outline of the original algorithm has been produced by Perdeck (2011) and is demonstrated in Figure 20.

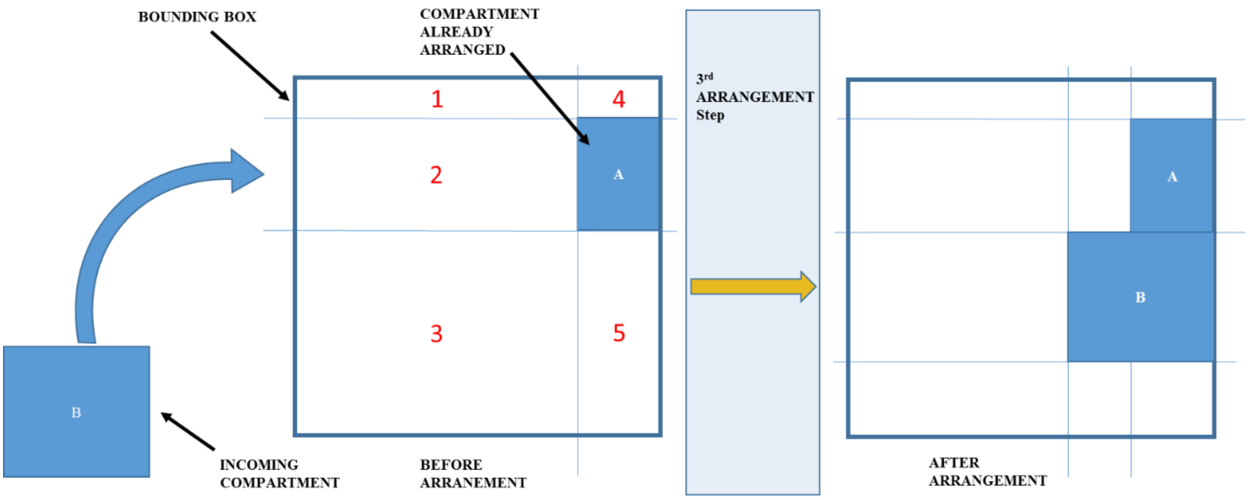

Figure 20 – The Original Version of the Arrangement Algorithm using Perdeck (2011)[1]

In Figure 20 the new incoming compartment being introduced (Compartment B) seeks to be as close as possible to the right-hand side of the bounding box (representing the pressure hull) without interfering with any other already arranged compartment. The locations (numbered 1 to 5 in Figure 20) are potential positions for the new compartment. Compartment B can be placed in any of the five locations, or a combination of adjacent locations, so long as they combine to form a rectangle. Compartment B cannot fit into boxes 1 & 4 as Compartment B has excessive height, so it must go in boxes 3 & 5.

The identification of free space within the pressure hull (as outlined in Figure 20) is performed using a dynamic grid. The modified algorithm used to identify free space creates a grid following the location of each compartment, which discretises the space within the pressure hull. Unlike the packing approach demonstrated by van Oers et al. (2009), the grid used in SUPERB's packing algorithm is capable of considering heterogeneous (i.e. unevenly spaced) grids. This is intended to reduce the amount of computation required to

[1] Figure 20 has been created by the Candidate and not Perdeck to show the original packing algorithm.

identify void spaces into which compartments could be packed, as space is mathematically described in an efficient manner by reducing the number of spaces stored by the computer.

The free space for an incoming compartment is assessed to determine where in the arrangement a compartment could be located. A matrix, describing where an incoming compartment could fit longitudinally, is generated and a second matrix is then generated for fitting within the height of the compartment. The two matrices are then overlapped to reveal the void space into which the incoming compartment could be arranged. This is then subjected to the generic packing rules (of the modified packing algorithm) to determine in which of the possible locations to place the compartment. The original packing algorithm's packing rules, which are intended to achieve maximum packing density regardless of a compartment's characteristics, have been replaced by this modification. The algorithm is now governed by the following four hierarchical rules (which do consider compartment characteristics and are hence generic):-

Rule 1. An incoming compartment must obey the geometric links to other compartments already placed. This is to meet any hard constraints applied to the incoming compartment. This rule will ensure that an incoming compartment will align with the other compartments, to which it is linked to via its (designer-defined) arrangement constraints.

Rule 2. The 'tendency' of the incoming compartment needs to be taken into account. Such as whether a compartment has the propensity to be located towards the bottom or top of the boat. This rule is used when there are multiple arrangement positions for an incoming compartment. The tendency is determined by the vertical position of the compartment, after the first two Arrangement Steps.

Rule 3. The incoming compartment's 'Vertical Constraint' must be obeyed. The Vertical Constraint is a restriction on the ability to vertically translate an incoming compartment. The compartment can have one of three designations. It can be assigned to a specific deck or be capable of moving up/down in one direction determined by its 'tendency' (see Rule 2). So for example, the Vertical Constraint is set so that trim tanks are assigned a specific deck, namely the Tankage Deck.

Rule 4. The arrangement should seek to achieve an even distribution of compartments in the transverse and vertical directions. The preferred position of the incoming compartment is determined by assigning those compartments that have been already arranged. This should produce arrangements that do not lead to a single deck being overloaded.

The purpose of the first three rules is to constrain the possible vertical and transverse translations of an incoming compartment, with the longitudinal constraint coming from the generation of the X-List. The fourth rule is intended to provide a decision process within the arrangement algorithm for selecting the preferred position of a compartment that now obeys all the imposed arrangement constraints (from the first two Arrangement Steps). With this approach, the packing rules relating to each compartment, as it is introduced to the layout, are both generic and alter dynamically. This meets the requirement considered necessary in Subsection 4.4.2.

4.5.4.ii Trial Runs of Compartment X-Listing

A series of trial runs of the Compartment X-Listing approach's third Arrangement Step (packing) were conducted. Their purpose was to work out how best to conduct the packing of compartments into a pressure hull (PH), using the X-List and the adopted packing algorithm. It was seen that during these trials, the arrangement of the internal compartments within a PH should be sequentially arranged from both ends of the boat. This helps to promote both weight and geometrical amidships balance for an arrangement. It was also concluded that packing towards amidships should reduce the possibility of voids forming within an arrangement. Voids would reduce an arrangement's packing efficiency and could lead to an arrangement not fitting inside the PH.

A further outcome of these trials was the production of a further piece of code within the computer program that carries out the third Arrangement Step. It updates the 'tendency' (see Rule 2 in the previous Sub-subsection) and Vertical Constraint (see Rule 3 above) assigned to compartments that are yet to be packed. That code was produced to ensure that compartments could be linked 'upstream' to compartments that have already been arranged. These compartments may have changed their vertical location following their own location in the arrangement.

4.5.5 JUSTIFICATION OF THE ORDER OF THE ARRANGEMENT STEPS

The order of Arrangement Steps shown in red in Figure 17 on page 94 is considered to be the only one which is viable. The first Arrangement Step addresses the Style Preferences and operates at the global level for the arrangement of compartments, so it cannot follow the Arrangement Step which is concerned with the locally applied Functional Constraints (Arrangement Step 2). This order ensures that the Functional Constraints are not violated by compartments being moved at the higher global level. The Arrangement Step addressing packing (Arrangement Step 3) has to be the final step in the sequence as the arrangement is fixed from this point. It would not be logically possible to apply any constraints on the arrangement after this step.

4.5.6 THE TIDY SUPPORT STEP

Of special importance amongst the Support Steps is the Tidy Support Step. The Tidy Support Step ensures that after packing (third Arrangement Step), compartments requiring pressure hull penetrations, such as the torpedo launch compartment, are located in a correct (i.e. feasible) way. This Support Step also seeks to eliminate any voids in the internal arrangement, while not significantly disturbing the relative positions (i.e. altering the arrangement style) of the already packed compartments. It achieves this by dividing into sections the (internal) arrangement and then packing these sections, while taking care not the significantly alter the relative positions of compartments. The Tidy Support Step is thus important, as it ensures the arrangements produced are conceivable – helping to meet objective 2.3 stated in Table 4 (Table of Research Proposal Objectives) in Subsection 2.7.3 on page 62.

4.5.7 ARRANGEMENT OF EXTERNAL COMPARTMENTS

The arrangement of compartments (tanks etc.) external to the PH should be strongly driven by the results of the internal arrangement, due to the geometric relationships between internal and external compartments. For instance, the external portion of torpedo tubes has to be adjacent to the torpedo launch compartment. Thus, the external compartments are not arranged by fully applying the Compartment X-Listing method. Instead, all the external compartments that have a geometric relationship with specific internal compartments are arranged and fixed. Another arrangement program, which has been devised specially for use in SUPERB and called SUPERB’s External Arrangement Program (SEAP), is then used in conjunction with an external Compartment X-List (but not using the internal arrangement method presented in this chapter) to complete the arrangement.

4.6 THE ANALYSIS MODULE OF SUPERB

4.6.1 NAVAL ARCHITECTURAL BALANCE

The ‘Analysis Section’ of SUPERB (the third stage in the single pass of the design procedure in Figure 15 on page 88) sets out to audit and then determine if the current design produces a naval architecturally balanced design. A design is considered valid by SUPERB (i.e. balanced to a concept level) if it meets all the criteria in the definition of naval architectural balance. Table 9 summarises the balance criteria used by SUPERB. At the concept level, the criteria for balance fall into three categories: resistance and powering, geometrical fit and hydrostatic balance, as per the definition of balance provided in Section 1.2.

The resistance and powering balance ensures that the vessel has sufficient power to generate the speeds required in overcoming the hydrodynamic resistance and propulsive losses, plus any appropriate hotel demands. The geometric balance simply ensures that all the compartments and equipment fit within the space provided by the vessel. This applies to the spaces both internal and external to the pressure hull(s). Finally, the hydrostatic balance has several components. A boat must be neutrally buoyant when fully submerged and it must have a centre of gravity sufficiently below and longitudinally and transversely coincident with the centre of buoyancy, to provide acceptable stability characteristics when resisting rolling, pitching and surfacing. Finally, the boat must be capable of maintaining a level trim for all operationally sensible loading conditions (i.e. the trim polygon must be sufficiently large).

Table 9 – The Criteria for Determining Naval Architectural Balance of a Submarine Design used by SUPERB

Criteria	Category	Definition	Allowable Tolerance
Design Speeds Achievable	Resistance & Powering	Design Speeds > Requirement Speeds	0.5 knots
Casing Width	Geometrical	Sufficient Casing Width Provided	2 %
Casing Height	Geometrical	Sufficient Casing Height Provided	2 %
Casing Length	Geometrical	Sufficient Casing Length Provided	2 %
Casing Volume	Geometrical	Sufficient Casing Volume Provided	2 %
PH Diameter	Geometrical	Sufficient PH Diameter Provided	2.5 %
PH Length	Geometrical	Sufficient PH Length Provided	2.5 %
PH Length (Tankage)	Geometrical	Sufficient PH Length Provided for Tankage	2.5 %
PH Volume	Geometrical	Sufficient PH Volume Provided	2 %
Comp. Overlap in PH	Geometrical	Ensure No Overlapping Compartments in PH	n/a
Submerged Density	Hydrostatic Balance	Submerged Density = 1.0275 kg/dm^3 in ST&C[1]	2 %
Trim Conditions	Hydrostatic Balance	Trim Polygon Sufficiently Sized to Maintain Trim in all Design Load Conditions	5 %
Roll Stability	Hydrostatic Balance	Vertical Distance Between C of B and C of G >4% of PH Diameter	0.5%
Pitch Stability	Hydrostatic Balance	Longitudinal Distance Between C of B and C of G <2.5% Casing Length	1.14 m

[1] ST&C – Standard Trim and Compensation Condition. This is defined in Appendix 3 of Burcher & Rydill (1994)

At the concept level, the definition of balance only needs to be consistent with the current level of the design definition. The acceptable tolerance for naval architectural balance at the concept level adopted in the studies using SUPERB is given in the last column of Table 9. These tolerances have been selected to be consistent with practice in the design studies in the postgraduate Submarine Design Course at UCL (NAME Office, University College London, 2014).

4.6.2 ANALYSIS LIMITATIONS

There are limits to the extent that analysis is appropriate at the concept level of design fidelity (Andrews, 1994). The lack of design detail and definition, which will be necessary later in the design process, makes it not possible to assess some criteria for naval architectural balance. For example, assessing the manoeuvrability of a submarine requires the definition of the geometry and location and configuration of all relevant appendages, such as hydroplanes. Such definition is normally beyond the scope of the analysis at the concept stage. Another key limitation is the predicted flow field around a moving SSH(N), which would need the generation of computationally extensive Computational Fluid Dynamics (CFD). However, it is also the case that the implications of such a flow field might be necessary to identifying preferred locations for the ingress and egress of UUVs, and this could then require early design investigation of a project specific requirement and design driver.

For some measures of performance, it is seen to be necessary to use a metric, which is known to be 'rough' but also useful to evaluate a design, even in the Concept Phase. This is in line with the purpose of the Concept Phase put forward by Andrews (2013) that analysis in the Concept Phase generally should be "cursory", but in some specific areas in a specific project, analysis might be required to be extensive to facilitate adequate concept exploration. An example of this is the level of stealth attributed to a submarine design. Accurately assessing the various signatures of a design (acoustic, electromagnetic, etc.) has been considered impossible with the likely level of design detail available at concept; nevertheless, a value needs to be placed on the level of stealth of a design, given it is of fundamental importance to a submarine's overall performance. To achieve this, a simplified model, which uses publically available data to predict the broadband emitted acoustic power, has been devised by the candidate and adopted for SUPERB. The model's construction is described in Appendix G.

The problem of the limited analysis possible during the Concept Phase of the ship/submarine design process has been explored by Andrews (2013). Andrews pointed out absolute answers from numerical analysis in the Concept Phase should not be treated as absolutes, but rather as indicative and the limitations of concept definition should be appreciated by the designer and so the risk of, possible but yet to emerge, constraints on the design should be clearly flagged. An example of such a constraint using SUPERB's analysis of designs might include a downstream need to change bridge fin or sonar locations due to an emergent hydrodynamic or manoeuvrability issues.

Andrews (2013) suggested that at the concept level of definition a comprehensive exploration should be carried out to identify likely constraints. Furthermore, Andrews also recommended that numerical results should not be taken 'at face value' in the decision-making when a given concept design was being selected for further design development, but rather the primary role of values at concept (given the poor granularity) is to inform the trade-off process. The implication for the use of SUPERB is that the concept design assigned the highest Measure of Tradable Performance Characteristics (MoTPC) should not necessarily be taken to be the 'best' design. Rather, a group of concepts with high values of MoTPC from the concept exploration stage should all be taken forward and tested in the trade-off studies. It is likely that the granularity between the designs (and therefore any MoTPC scores) will exceed the discernible difference in design definition and performance assessment at this stage of design. Furthermore, should a crucial, and previously undetected, constraint emerge in subsequent studies, the designer should be prepared to return to concept exploration in order to focus on the emergent constraint and retest the trade-off results and choices made.

CHAPTER 5 - VALIDATING SUPERB

5.1 CREATING EXISTING BENCHMARK DESIGNS IN SUPERB

This chapter covers the validation of the SUPERB tool and in particular, the novel arrangement method used in SUPERB: Compartment X-Listing. A systematic validation of SUPERB was undertaken to give confidence that it can act as a 'generic' submarine design tool as outlined in the objectives (Subsection 2.7.1). Three main validation steps have been employed, using benchmark designs. These benchmark designs are both real world submarines and (naval architecturally balanced) concept designs. The chapter concludes with a demonstration of SUPERB's ability to produce concept designs with unusual physical features and uses the Compartment X-Listing approach to produce an arrangement for a balanced concept level design study.

5.1.1 BENCHMARK WEIGHT VALIDATION

Confidence in SUPERB was obtained by comparing SUPERB-generated 'interpreted'[1] designs against a range of existing designs. The SUPERB-generated designs were considered fair comparisons to their benchmark counterparts if they were shown to have similar characteristics to the benchmark design and a plausible layout, which had been used to obtain a balanced design at the early-stage concept level.

An example SSN is used in UCL's postgraduate Submarine Design Course (NAME Office, University College London 2014) to demonstrate the course's design procedure (NAME Office, University College London, 2012c). It is 5,000 tonnes and is illustrated by Figure 21. As with all submarine designs shown in this thesis, the following compartment function colour coding applies: red = fight, yellow = propulsion, green = infrastructure, blue = float and purple = UUVs and ICBMs. All the SUPERB-generated submarine designs produced by the candidate as part of this thesis are summarised in Appendix H.

[1] Interpreted in this research refers to design characteristics of a design being programmed into SUPERB by the candidate. An actual design ought to be as accurately represented as possible by SUPERB, within the confines of its programming. For instance, SUPERB has recreated the RN's *Trafalgar*-class SSN in the next subsection. The forward hydroplanes actuation equipment are located (in the actual design) in a gap in the forward Main Ballast Tank (MBT) which is configured in a backwards 'C' shape (conformed within the dome bulkhead). However, SUPERB cannot currently represent this without modification specific to a design, so the forward hydroplane actuation equipment and MBT are effectively combined into a one SUPERB 'compartment'.

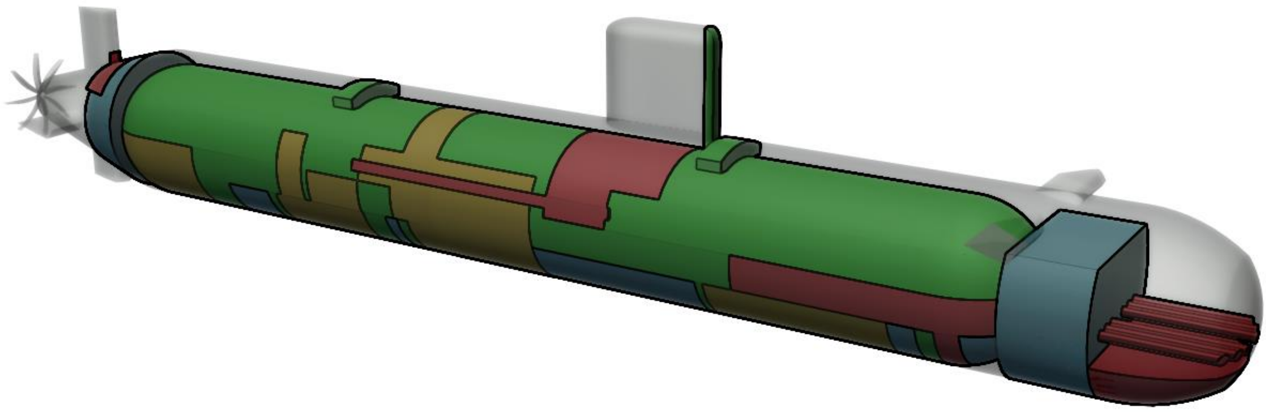

Figure 21 – SUPERB Generated UCL 5,000 Tonne SSN

It order to validate SUPERB, UCL's 5,000 tonne example SSN[1] has been regenerated using SUPERB and its weight breakdown compared to the one provided as part of the UCL's postgraduate Submarine Design Course. An auditing subprogram in SUPERB creates a one digit weight breakdown. The comparison is shown in Table 10.

Table 10 – Weight Breakdown Comparison between UCL Benchmark and SUPERB[2]

Weight Group	UCL Benchmark SSN Weight [Tonne]	SUPERB SSN Weight [Tonne]	Difference [% of Total Weight]
Total	5219	5215	0.08
1. Structures	2364	2445	-1.55
2. Propulsion Systems	630	644	-0.27
3. Electrical Services	154	210	-1.07
4. Control & Communications	89	53	0.69
5. Submarine Services	345	268	1.48
6. Outfit & Furnishings	133	136	-0.05
7. Armaments & Pyrotechnics	124	141	-0.33
8. Fixed Ballast	420	405	0.29
9. Variable Items	960	915	0.86

The comparison between the two weight breakdown profiles shows a good level of agreement between the two designs. This is an indication that the equations and algorithms used in the Mathematical Modelling Module of

[1] In Figure 21, a void between the forward Main Ballast Tank (MBT) and the Pressure Hull (PH) can be seen. This is due to the modelling of compartments as blocks in SUPERB with straight lines. Thus, it cannot represent the more complex geometry of the forward MBT wrapping around the PH. To ensure that the forward MBT partially wraps around the PH, so a portion of the oversized forward MBT compartment (as it is shown in Figure 21) is not be taken into account during analysis, due to the PH.
[2] UCL Weight Breakdown Data taken from NAME Office, University College London (2012b)

SUPERB described in Section 4.3 are valid for a 'conventional' SSN. The slight discrepancies are due to the SUPERB generated SSN being marginally larger to achieve naval architectural balance and due to the slight difference between the two design methods. The weight breakdown suggests that novel concept designs generated in SUPERB may also be produced with believable weight breakdowns, providing sufficiently indicative designs at the concept level.

5.1.2 VALIDATION OF ARRANGEMENT THROUGH EXAMPLE SUBMARINE DESIGNS

5.1.2.i Introduction

Two existing example submarine designs have been reproduced using SUPERB to provide a degree of assurance that the novel arrangement approach, developed as part of SUPERB can produce valid and conceivable submarine arrangements. By 'valid' it was considered that the designs produce arrangements that are naval architecturally balanced, as per SUPERB's balance criteria outlined in Table 9. It followed that since it is known that real-world designs are naval architecturally balanced, then the arrangements produced by SUPERB, using similar physical features and arrangement of compartments containing similar equipment, should be sufficiently believable to validate the SUPERB's arrangement approach (Compartment X-Listing). This validation exercise is not intended to copy necessarily the same styles as those of these benchmark designs. The two example submarines that were selected are[1]:

1. A 5,000 tonne SSN, similar to the UK's *Trafalgar*-Class (see Figure 22 on page 110)
2. A 9,000 tonne SSBN, similar to the French *Redoutable*-Class (see Figure 23 on page 111)

[1] The SUPERB generated versions of the benchmark designs have been reconstructed in Paramarine for analysis and are presented in the figures.

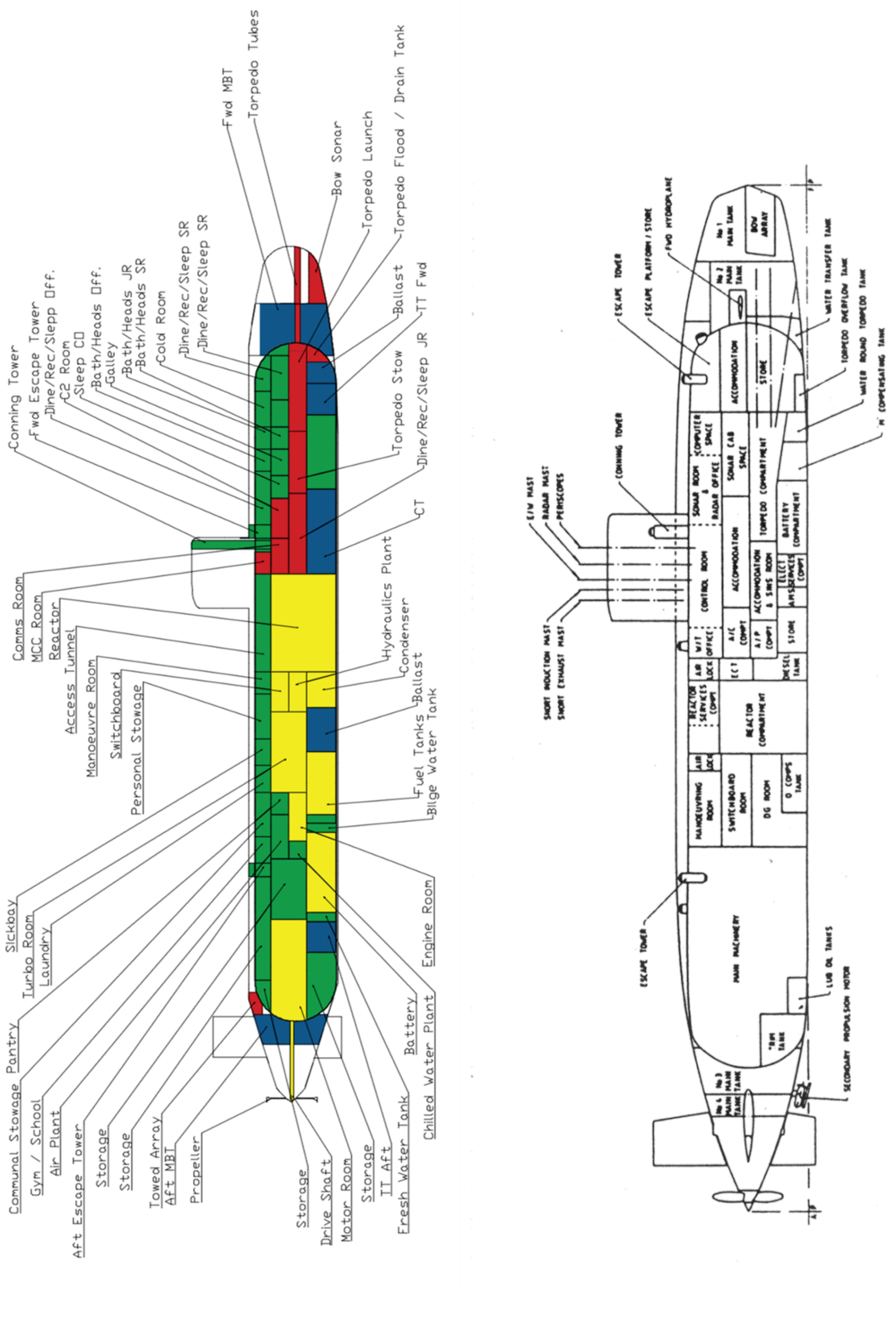

Figure 22 – SUPERB Generated 'Trafalgar-Class' Example Submarine and Trafalgar-Class Arrangement (NAME Office, University College London, 2014)

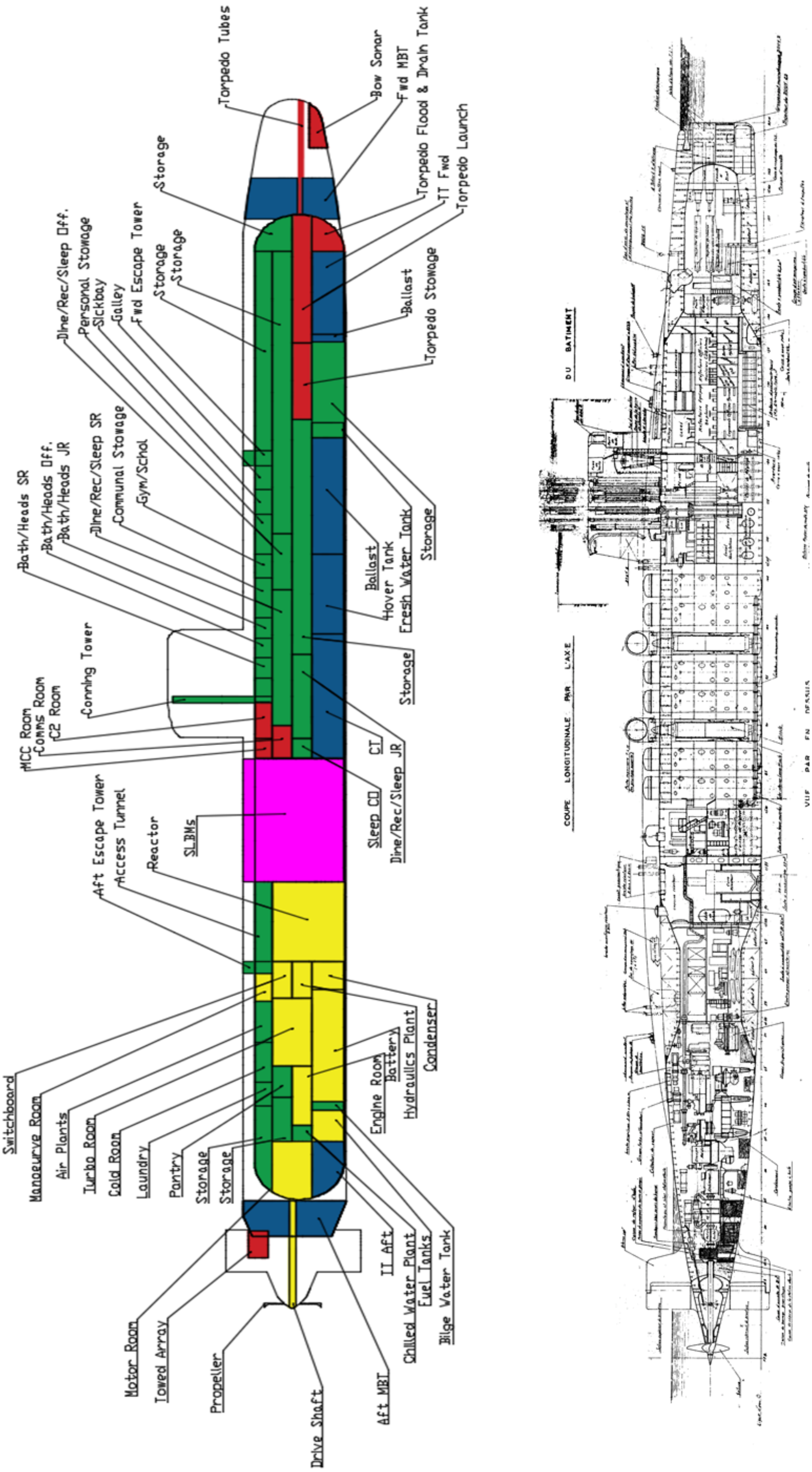

Figure 23 – SUPERB Generated 'Le Redoutable-Class' Example Submarine and Redoutable-Class Arrangement (Service Historique de la Défense, 2008)

5.1.2.ii Comparing the SUPERB Produced and Real-World Example Submarines

Table 11 – Top-Level Characteristics of Example Submarines and SUPERB Designed Counterparts[1]

Example Submarine Class		Trafalgar (UK – 1983)			Redoutable (France – 1971)		
Characteristic	**Units**	SUPERB Analysis Module[2]	Paramarine Analysis	Actual	SUPERB Analysis Module	Paramarine Analysis	Actual
Submerged Displacement	**Te**	5300	5371	5300	8940	9174	8940
ROB	**%**	10.4	9.0	10.4	11.1	8.4	11.1
Deep Diving Depth	**m**	600	600	600	300	300	300
Overall Length	**m**	100.8	100.9	85.4	160	158.9	128.7
Beam	**m**	10.6	10.61	9.8	10.6	11.61	10.6
Top Speed (Submerged)	**Knots**	34.4	28.2	30	21.4	28.4	25
Installed Nuclear Power	**MW**	33.5	33.5	31.9	15.0	15.0	12
Number of Nuclear Reactors	**n/a**	1	1	1	1	1	1
Number of Steam Turbines	**n/a**	2	2	2	2	2	2
Number of Turbo Generators	**n/a**	2	2	2	2	2	2
Number of Shafts	**n/a**	1	1	1	1	1	1
Total Installed Diesel Power	**MW**	3.4	3.4	2.1	4.4	4.4	0.9
Number of DGs	**n/a**	3	3	2	4	4	2
Number of HWT/TLAM	**n/a**	40	40	30	8	8	18
Number of Torpedo Tubes	**n/a**	4	4	5	4	4	4
Complement	**Men**	87	87	97	115	115	115
BG (Longitudinal)	**m**	1.08	0.237	n/a	0.13	1.92	n/a
BG (Vertical)	**m**	0.92	0.322	n/a	1.13	1.173	n/a

The two example submarines arrangements generated by SUPERB, have top-level characteristics close to their real-world counterparts, as shown in Table 11. This indicated that the comparison between the SUPERB and

[1] References for Table 11: (ArmedForces.co.uk, 2014) (Naval-Technology.com, 2014d) (Netmarine.Net, 2014) (World_Nuclear.com, 2014) (Military-Today.com, 2014b)
[2] Some stated variables in SUPERB's Analysis Module, such as DDD, are the same as the actual and Paramarine analysis values because they are top-level inputs for SUPERB.

real-world designs was reasonable. There are two reasons why the SUPERB generated design characteristics were not expected to be identical to those of the real-world designs. Firstly, the data used in SUPERB is unclassified and largely taken from the UCL Databook for Submarine Design (NAME Office, University College London, 2012b), which is intended to be realistic but not completely precise. It should also be noted that the data from the real world submarine examples is from designs now some 40-50 years old, whereas SUPERB reflects some subsequent improvements in technology.

Secondly, the submarines generated by SUPERB are only at a concept level of definition, while the real-world counterparts are fully developed designs of what were/are in-service submarines. The real-world designs will have been subjected to a wider variety of detailed design decisions as they progressed right through the design process. Some of the top-level characteristics of the SUPERB studies are identical with the real-world submarines, due to these characteristics being input variables into SUPERB, and hence were fixed using those values.

The mathematical relationships used in SUPERB's Mathematical Modelling Module outlined in Section 4.3, have produced designs that could be improved by future modifications to these relationships and should ensure designs, generated in the future using SUPERB, would be more realistic. For example, SUPERB has generated the *Redoutable*-Class SSBN example (shown in Figure 23) with an overall length of 160 m, compared to the real-world submarine's value of 128.7 m. This is because the casing of the SUPERB design has been oversized as a result of a larger pressure hull, and improvements to the mathematical relationships are required to reduce it, as currently SUPERB cannot consider pressure hull transitions[1]. It was considered that improving SUPERB to model pressure hull transitions would push SUPERB to produce a more 'realistic' overall length for its version of Redoutable. This issue is discussed in Subsection 8.3.4 and a possible method for modelling pressure hull transitions is proposed in Subsection 9.2.3. The extended length was considered to be the reason that the power of the nuclear reactor has been calculated to be 15 MW (due to the poorer hydrodynamic performance of the hull), rather than the 12 MW in the last column of by Table 11. Another reason for the inflated value for the reactor power could have been possible inaccuracy in the data. For instance, the maximum submerged speed

[1] A pressure hull transition is the linking section of pressure hull between two other sections of differing diameters.

is 25 knots from the quoted source. However such information is usually highly sensitive and difficult to verify from the open literature. Similarly, the approximate 15-metre difference in LOA values for the *Trafalgar*-class SSN can be explained by the inability currently of SUPERB to model decks which are not evenly spaced throughout the length of the boat. SUPERB's 'crude' modelling also explains the reduced Reserve of Buoyancy (RoB) for both examples when analysed by Paramarine. As previously stated, SUPERB oversized the MBTs due to its limitations in modelling the complex geometric interface between MBT and PH bulkhead. Conversely, Paramarine can model this interface more accurately. Thus, the MBT volume is reduced, and so the RoB is decreased as a result.

5.1.3 COMPARING THE ARRANGEMENTS FROM DESIGNS GENERATED BY SUPERB TO REAL-WORLD EXAMPLES

The two SUPERB generated submarines have both also been replicated in Paramarine, and both have been independently assessed by Paramarine as being naval architecturally balanced to a concept level (see Table 11) using the criteria in Table 9 on page 104. This indicates that the approach is capable of producing arrangements that are balanced and could be used in a design study investigating SSH(N) concepts.

The arrangements generated using SUPERB appeared to be conceivable arrangements, while not being identical to their real-world counterparts. This was expected since the arranged compartments have similar but not identical design characteristics. For instance, both *Trafalgar* submarine designs have similar personnel numbers, which are likely to lead to similarly sized accommodation compartments to arrange. This was unsurprising as a real-world submarine has been subjected to considerably more design decisions and trade-offs than a SUPERB generated submarine design.

The Compartment X-Listing approach relies on a profile of Style Preferences and Functional Constraints which are intended to ensure that a conceivable and naval architecturally balanced arrangement is produced. The collection of Functional Constraints and Style Preferences selected has been termed the "Constraint Profile". It follows that the selection of the constraints in such a Constraint Profile affects the arrangement produced using Compartment X-Listing. As a first step in the validation process for Compartment X-Listing, the Constraint Profile selected for the generation of the two example real-world submarines by SUPERB was highly restricted. This was done to ensure the arrangements produced using SUPERB would be orthodox in style. Ensuring agreement with the orthodox style was an indication that real-world arrangements of the example submarines could be replicated. The first validation step was to determine that Compartment X-Listing could produce conceivable arrangements in at least some circumstances. Thus, a Constraint Profile was chosen to promote the production of an orthodox style of arrangement, which is already known to have a good chance of producing balanced arrangements. This first validation step did not fully validate the Compartment X-Listing approach, as it did not indicate that it is a (mostly) generic approach, as described in Subsection 4.4.2.

5.2 COMPARISONS AGAINST UNORTHODOX BENCHMARK DESIGNS

5.2.1 INTRODUCTION

The next step in the validation of the Compartment X-Listing approach was to demonstrate that the approach could handle the arrangement of compartments containing equipment and physical features that were noticeably less orthodox. It was considered that the arrangement approach should be able to handle a wide variety of inputs (i.e. the compartments on which arrangement is performed) if it is to be able to tackle a wide range of potential submarine configurations. To reiterate, the definition of 'unorthodox' in this research project is defined as the consideration of novel physical features or set of arrangement relationships which yield a concept design that significantly differs from orthodox (i.e. currently prevailing) design trends. If a design calls for the incorporation of unorthodox design features, it follows that the design's arrangement would also be unorthodox, with features such as a large number of UUVs.

5.2.2 VALIDATION

5.2.2.i Bradbeer's SSKN

Bradbeer (2015) proposed a nuclear-battery-powered hybrid submarine to fill the gap between high-performance nuclear-powered attack submarines (SSNs), which come with a relatively expensive price tag (typically £1 billion), and cheaper (non-nuclear) Air Independent Propulsion (AIP) attack submarines (SSKs). This results in a much reduced intermediate capability and was designated an SSKNs. Bradbeer's concept is a halfway design that uses a small (and relatively cheaper) nuclear reactor, to provide long submerged endurance base power supply for the hotel load and cruise speeds, and a large modern (AIP) battery, to provide boost power for short-term sprint speeds.

Usefully, Bradbeer used the procedure from UCL's submarine design course (NAME Office, University College London, 2014), which has also been used to a substantial degree in developing SUPERB (see

Subsection 2.4.2). Effectively, the design procedures used by the candidate and Bradbeer have a high degree of commonality – especially concerning the modelling of compartments and major equipment.

Table 12 – Principal Characteristics of an SSKN Proposed by Bradbeer (2015)

Displacement	4,354 te surfaced, 4,833 te submerged
Unit Procurement Cost (UPC)	£ 627 Million (2008 price level using UCL data)
Pressure Hull Dimensions	56.3m long, 10m diameter
Propulsion Plant	Pressurised Water Reactor (PWR) developing 14.6 MW thermal power, providing 1.5 MW shaft power through rafted main turbines and gearbox, with 8.4 MW sprint boost motor.
Speeds	15 knots sustained, 28 knots for one hour on battery
Battery	35 GJ (9.8 MWh) Lithium-ion HEDB, weighing 98 tonnes
Battery recharge time	8 hours at slow speed, submerged (On Reactor)
Submerged BG	0.49 m
Payload	4x533mm tubes, 20 reloads, 2 water ram systems. Bow sonar and passive ranging sonar (flank mounted). 6 masts (search, attack, comms, radar, EW, snort). 2 buoyant VLF antennas.
Complement	116: 19 officers, 39 senior rates, 58 junior rates
Accommodation standard	2-watch system with nuclear watchkeepers on 3-watch system. Accommodation sized to match Royal Navy standard.

The arrangement for Bradbeer's SSKN was primarily directed by the designer, through the creation and control of a Microsoft Excel spreadsheet. The spreadsheet was capable of both performing calculations in accordance with the UCL submarine design procedure, to balance the design hydrostatically, and to automatically resize some compartments. The arrangement style and compartment locations were pre-defined by Bradbeer. The SSKN proposed by Bradbeer is described in Table 12.

5.2.2.ii Recreating Bradbeer's SSKN in SUPERB

As further validation of SUPERB (especially Compartment X-Listing), SUPERB was used to interpret and recreate the SSKN proposed by Bradbeer (2015). Due to this unorthodox design, some of the inputs to Compartment X-Listing were altered by modifying the Mathematical Modelling Module of SUPERB.

Table 13 – One-Digit Breakdown[1] Comparison between the SSKNs Produced by Bradbeer and SUPERB

Weight Group	Mass (Tonnes)		Difference
	Bradbeer's SSKN	**SUPERB's SSKN**	**(% of Total Weight)**
1	1948	2014	-1.38
2 [2]	607	465	2.96
3	152	249	-2.02
4	70	50	0.42
5	294	263	0.65
6	126	106	0.99
7	113	178	-1.36
8 [3]	769	568	4.19
9	756	901	-3.03
Total	4835	4794	0.85

To check that the Mathematical Modelling Module of SUPERB had been successfully modified to recreate Bradbeer's SSKN, the weight breakdowns of the original design and SUPERB's version have been compared (see Table 13). These breakdowns largely agree with one another, and so it was concluded that SUPERB could successfully model novel a submarine concept. The slight discrepancies were attributed to some equations and balancing processes in the Mathematical Modelling Module being similar, but not identical, to those used by Bradbeer. Furthermore, at the concept level of definition there is a lack of design fidelity (Andrews, 1994) that omits assigning some (typically smaller) equipment items to specific weight groups. There were also discrepancies in predicting the weight group distribution of some equipment in the absence of explicit knowledge.

Once it was established that SUPERB arranged broadly similar compartments into a similarly sized geometric space (i.e. the inputs to the arrangement approach), the arrangement process in SUPERB was generated. As a validation exercise, Bradbeer's SSKN was recreated using a Constraint Profile that was more restrictive and the same as that used in Subsection 5.1.2. This Constraint Profile promoted an arrangement that was considered orthodox (i.e. consistent with traditional practice), so the arrangement produced by SUPERB was more constrained. The Functional Constraints that have been partly used to make up the Constraint Profile are listed in Table 14.

[1] Same weight group definition as Table 10 on page 124
[2] SUPERB and Bradbeer's approach required assigning secondary propulsion equipment to different weight groups – hence the discrepancy between the two weight breakdown profiles. However, the combined totals for Weight Groups 2 and 3 approximately agree.
[3] To achieve naval architectural balance (which is more comprehensive than that in (Bradbeer, 2015), SUPERB has removed all the fixed ballast in Weight Group 8 and replaced with variable ballast in Weight Group 9.

Table 14 – Functional Constraints Applied to Generate Internal Arrangements with Compartment X-Listing

Description of Constraint	Applied for More Constrained Arrangements	Applied for Less Constrained Arrangements
Primary Engine Near Amidships (if applicable)	✓	✗
Tanks & Batteries located in Tank Deck	✓	✓
Ensure Tankage Compartment Order the Correct Way Around (Aft to Forward)	✓	✓
Aft Trim Tank is most Aft Tank	✓	✓
Forward Trim Tank is most Forward Tank	✓	✓
Compensation and Hover Tanks (if applicable) near Amidships	✓	✗
One Battery Set Aft and One Forward of Primary Engine	✓	✗
Turbomachinery Adjacent (Aft) to Primary Engine (if applicable)[1]	✓	✗
Motor Aligned and Aft of Turbomachinery (if applicable)	✓	✓
Motor Penetrates Aft End of PH and Aligned with Propeller Shaft	✓	✓
Manoeuvre Room Above Turbomachinery	✓	✗
Condenser Adjacent to RC (if applicable)	✓	✗
Switchboard Aft of Primary Engine[2] and Above Non-Nuclear Engine	✓	✗
Internal O2 and Fuel Tanks Adjacent to Non-Nuclear Engine (if applicable)	✓	✗
Accommodation & Stowage Forward of Primary Engine (Except Exceptions List[3])	✓	✗
Category A UUV Stowage and LARS Forward of Primary Engine[4]	✓	✓
Category A UUV Stowage and LARS Penetrates Top Side of PH (if applicable)	✓	✓
Category B & C UUV Stowage and LARS above Torpedo Stowage and Launch	✓	✓
Category B & C UUV LARS Penetrate PH	✓	✓
Category B & C UUV LARS Penetrate Forward End of PH	✓	✗
Category B & C UUV Stowage Adjacent (Aft) of LARS	✓	✓
Torpedo Launch (Including Tubes) Penetrate Forward End of PH	✓	✓
Torpedo Stowage Adjacent (Aft) of Torpedo Launch (Including Tubes)	✓	✓
All Command and Control Compartments[5] Adjacent to One Another	✓	✓
Commanding Officer's Accommodation Adjacent to C2 Room	✓	✗
Conning Tower Adjacent to Control Room[6]	✓	✗
One Escape Tower Aft and One Forward of Primary Engine	✓	✓
Escape Towers and Conning Tower Penetrate Top of PH	✓	✓
Access Tunnel Located Above RC (if Applicable)	✓	✓
Outfit and Stowage Compartments[7] Located Aft of Primary Engine are Located above Propulsion Compartments	✓	✗

[1] Turbomachinery applicable for nuclear reactors (RCs) and closed cycle steam turbines (CCSTs).
[2] For non-nuclear submarines, the primary engine is also the non-nuclear engine. The secondary engine will also be located within that compartment.
[3] Personal Stowage, Communal Stowage, Pantry, Cold Room, Gym & School, Laundry, Sickbay, Water Plants, Air Conditioning Plants, Hydraulic Actuation Plants and Garbage Ejector.
[4] If Category A UUVs stowed internally.
[5] MCC Room, Control Room and Communications Room make up the command and control compartments for a submarine.
[6] This was included because it was present on the *Trafalgar*-class submarine, which has been used as a benchmark design in this research. It is acknowledged that with the advent of non-penetrating masts, such as those on the Astute-class, this Functional Constraint may no longer be necessary if designing a modern submarine.
[7] Except fresh water and bilge water tanks.

This investigation is a further validation of SUPERB's ability to produce an orthodox arrangement for a reasonably unorthodox design – but not necessarily for a much more extensive range of designs. The arrangement produced is displayed in Figure 24 and can be compared to Bradbeer's (more limited) original shown in Figure 25.

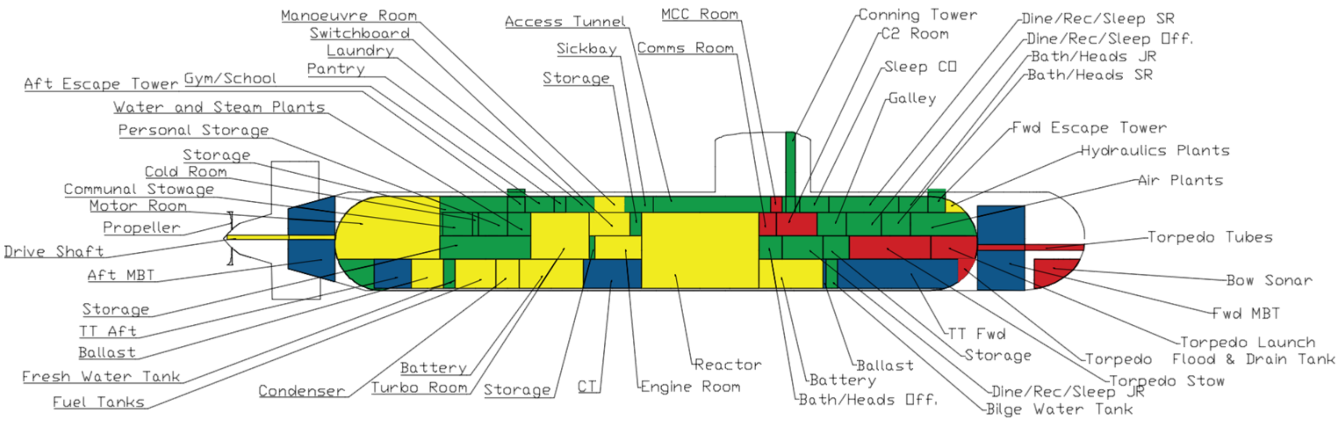

Figure 24 – Section View of SUPERB's Version of Bradbeer's SSKN Concept (with a More Constrained Arrangement)

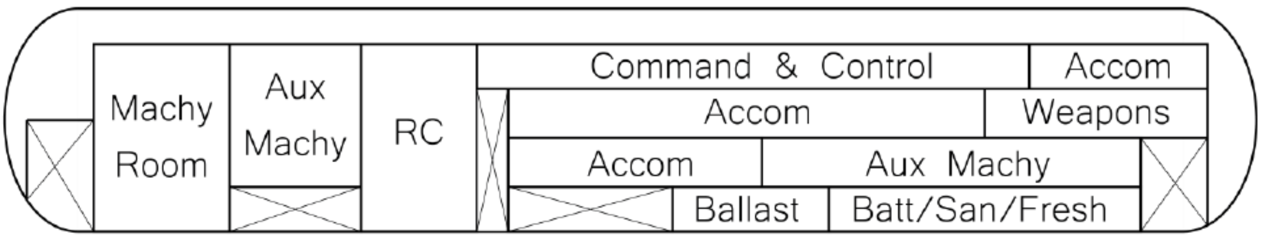

Figure 25 – Internal Arrangement of an SSKN Proposed by Bradbeer (2015)

In comparison between the two arrangements of Figure 24 and Figure 25, there are some discrepancies – suggesting that Bradbeer's arrangement does not entirely represent an orthodox style. For example, in Bradbeer's design the battery compartment was combined into one set of cells and not split into aft and forward halves. This was presumably done to counterbalance the Reactor Compartment (RC), which was located further aft than is usual in an SSN. Usually, the RC is located amidships to reduce its influence of the longitudinal moment, although machinery location considerations are also relevant.

5.2.2.iii Recreating Bradbeer's SSKN in SUPERB with a Relaxed Constraint Profile

To validate further SUPERB's arrangement method, Bradbeer's SSKN was again recreated using SUPERB. However, for this second recreation, the Constraint Profile was relaxed (i.e. some of the imposed constraints were eliminated). All the constraints eliminated for this investigation were Functional Constraints associated with second Arrangement Step outlined in Subsection 4.5.3. The list of Functional Constraints for both arrangements has been described in Table 14. The relaxed Constraint Profile uses the "less-constrained" set of Functional Constraints. This was to focus on the effects of altering the Functional Constraints on the arrangement produced by SUPERB. The resultant arrangement is displayed in Figure 26.

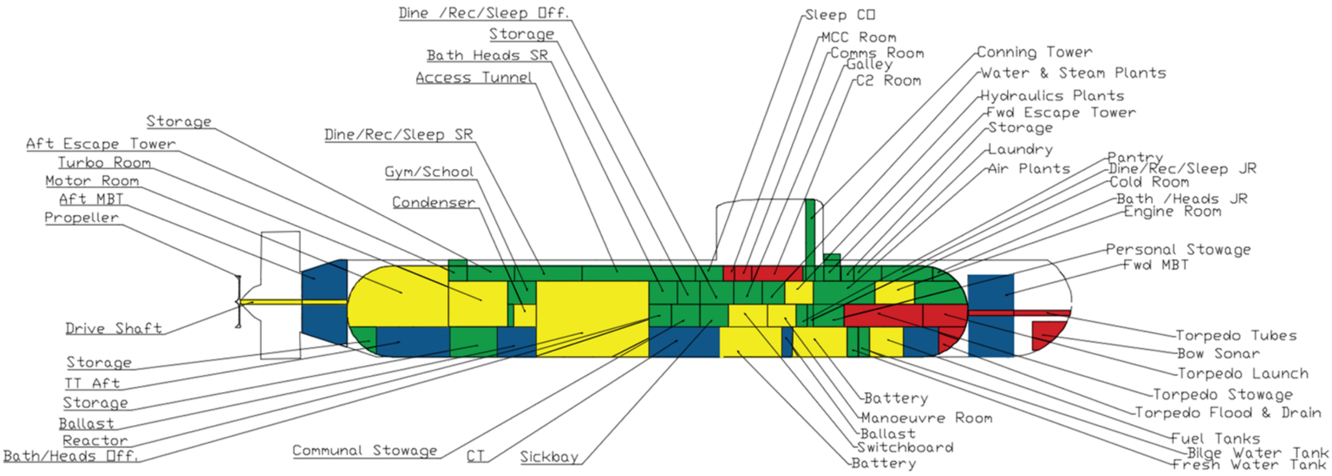

Figure 26 – Section View of SUPERB's Version of Bradbeer's SSKN Concept (with a Less Constrained Arrangement)

The arrangement produced (in Figure 26) from SUPERB using a more relaxed Constraint Profile was found to be similar to the Bradbeer's generated version in Figure 25. For example, the RC longitudinal location agrees with Bradbeer's version, as it has been moved further aft. In addition, the computer-based Compartment X-Listing approach almost combined the battery compartments together and forward of the RC, as in Bradbeer's version and unlike the first arrangement from SUPERB (Figure 24), where a more restrictive Constraint Profile was imposed.

Another similarity is that both Bradbeer's version and the arrangement of Figure 26 show the command and control (C2) compartments located together on the topmost deck. This is unlike the arrangement produced by SUPERB with the more restrictive Constraint Profile adopted in the previous subsection, resulting in a more limited longitudinal space forward of the RC and above the tankage deck. This then led to the C2 compartments to be spread across two decks.

The overall agreement between the original SSKN produced by Bradbeer and the arrangement produced by SUPERB, when a relaxed Constraint Profile was adopted, indicated that relaxing the Constraint Profile could potentially facilitate the generation of unorthodox arrangements in SUPERB. The "SSKN" by Bradbeer was considered unorthodox and so it could be concluded that a largely similar arrangement to the SUPERB generated arrangement (adopting the relaxed Constraint Profile) could have been considered sufficiently unorthodox. Furthermore, the consistency in the arrangements suggested that SUPERB could reasonably well replicate the actions of the (human) designer, which was considered fundamental if a large number of concept designs were to be generated by SUPERB with some confidence.

This validation of Compartment X-Listing's ability to generate unorthodox arrangements only examined the selection of Functional Constraints in the Constraint Profile. The effect on the generated arrangement of selecting Style Preferences from the first Arrangement Step is considered in the next section of this chapter, in order to determine if Compartment X-Listing would be capable of generating demonstrably unorthodox arrangements.

5.3 GENERATION OF UNORTHODOX CONCEPT DESIGNS

5.3.1 INTRODUCTION

An investigation was undertaken to determine whether the arrangement generated in SUPERB was sufficiently independent, or essentially dependent, on Style Preferences selection. It was decided that the first two Style Preferences in Figure 18 on page 96 that promote denser compartments towards the bottom and amidships of a boat should not be altered, as they encourage good hydrostatic balancing and stability. The latter is a fundamental design principle of submarine design and so essential in generating a naval architecturally balanced arrangement. However, the 'logistical effort' Style Preference was intended to be driven by design decisions by the designer, and these decisions would affect the arrangement style. For example, the designer could specify a level of attraction or repulsion between accommodation and propulsion compartments.

SUPERB was modified to incorporate a hypothetical technology where there was not likely to be any no pre-existing knowledge to guide the setup of the 'logistical effort'. The selected hypothetical technology was a teleport technology. UUVs were not selected as the new technology, as incorporating that technology would come with some existing knowledge that could bias the setup of the 'logistical effort'. Using a hypothetical teleportation technology was considered to prevent this bias and ensure it was only a 'thought experiment'.

It was considered that a second reason for not including UUVs was that the potentially large size of the UUV payload and accompanying equipment (suggested in Section 3.7 to be typically 50 to 150 tonnes) could hinder analysis of the generated arrangement. This arrangement could have been influenced by the relationship between the UUV-related compartments and the rest of a vessel – which have not yet been properly investigated. The hypothetical teleport technology was specified so that it would make a more limited impact on the space demanded by the (internal) compartments when placed in a layout for the investigation.

5.3.2 THE HYPOTHETICAL SCENARIO

As a near future speculation, it was supposed that a teleportation technology has been invented and developed and assumed applicable to two identical blocks of 3-metre cubes (called A and B), each with a mass of 10 tonnes. Effectively, these are black boxes with a 'magic' feature. In this investigation, the cubic blocks could be placed anywhere in the submarine, which removed any consideration of Functional Constraints for the teleport blocks. The set of Functional Constraints were the same as the "less constrained" set stated in Table 14. These were adopted to ensure that the unorthodox arrangements could be generated in the investigation, as seen in Sub-subsection 5.2.2.iii. Given the near-future point in time, it was assumed that no other modification to the Mathematical Modelling Module of SUPERB would be required, with the rest of the compartments having the same positional relationships with regard to the 'logistical effort' as has been assumed for the UCL 5,000 tonne SSN benchmark (see Subsection 5.1.1).

Table 15 – Design Characteristics of AIP SSK used for a Hypothetical Teleportable SSK

Characteristic	**Value**
Submerged Displacement [Tonnes]	5000
Reserve of Buoyancy [%]	10
Deep Dive Depth [m]	4000
Primary Propulsion	APEM Fuel Cell[1]
Primary Power [MW]	7.3
Maximum Speed [Knots]	22.5
Transit Speed On Primary Propulsion [Knots]	6
Maximum Range On Primary Propulsion [nm]	4000
Secondary Propulsion	Diesel
Secondary Power [MW]	1.4
Number of Torpedo Tubes	4
Number of Torpedo & ASM	36
Number of TLAM (VLS)	20
Number of Crew	53
Patrol Days	30

[1] APEM stands for Advanced Proton-Exchange Membrane. It is a fuel cell technology, similar but more advanced form of the Proton-Exchange Membrane (PEM) fuel cell technology (see fuelcelltoday.com (2014)).

The teleportation technology was also considered able to eliminate the operational advantage of extended endurance from nuclear reactors, so the teleportable submarine is an Air Independent Propulsion (AIP) SSK. Thus, the teleport-capable vessel has been designated to be a Submersible Ship Teleport (SST). A design implication of the operational advantage of instantly teleporting the SST to a location is that the number of patrol days could be reduced to 30 days. This, in turn, would reduce the volume of the SST assigned to accommodation and stores as crew levels would be decreased. Consequently, the volume freed up could be allocated to additional propulsion and weapon items. The characteristics of the hypothetical SST used in the investigation are outlined in Table 15.

The locations of the teleport blocks were assumed to be driven by their operation and thus considered unknowable in the hypothetical scenario. Thus, it was assumed that the teleport blocks would have a randomised level of attraction between each other and with all other types of compartment (e.g. accommodation). Each level of attraction could have been any value between -1 (full repulsion) to +1 (full attraction) and was incorporated into the stiffness matrix (K), which has been described in Subsection 4.5.2 and drives the selection of compartment locations.

5.3.3 A SUPERB DESIGN INVESTIGATION FOR A HYPOTHETICAL DESIGN CONCEPT

5.3.3.i Setup of Investigation

One hundred SST options were generated by SUPERB, with each one having a different profile of compartment location relationships to ‘optimise’ the ‘logistical effort’. It was considered that one hundred arrangements were sufficient to discern any trends. The results have been collated and displayed in Figure 27 and Figure 28. The Functional Constraints subsequently applied to the generated arrangements were selected so that the Constraint Profile was the ‘relaxed’ profile outlined in Table 14. All the SSTs produced for this investigation were naval architecturally balanced to an early-stage concept level. However, it was considered that the arrangements did not strictly have to be naval architecturally balanced for this investigation given what was of interest was the degree of influence the setup of the ‘logistical effort’ Style Preference had on the studies’ arrangements, rather than the ability to produce concept level arrangements that were appropriately balanced.

5.3.3.ii Verification of the Randomised Relationships for Compartments in the Hypothetical Investigation

To ensure that the location relationship (level of attraction or repulsion) between the two ‘teleport blocks’ themselves and each type of the putative SSTs’ compartments had been randomly assigned during the generation of the 100 arrangements by SUPERB, the normalised[1] locations of the 'teleport blocks' centroids were plotted and are shown in Figure 27.

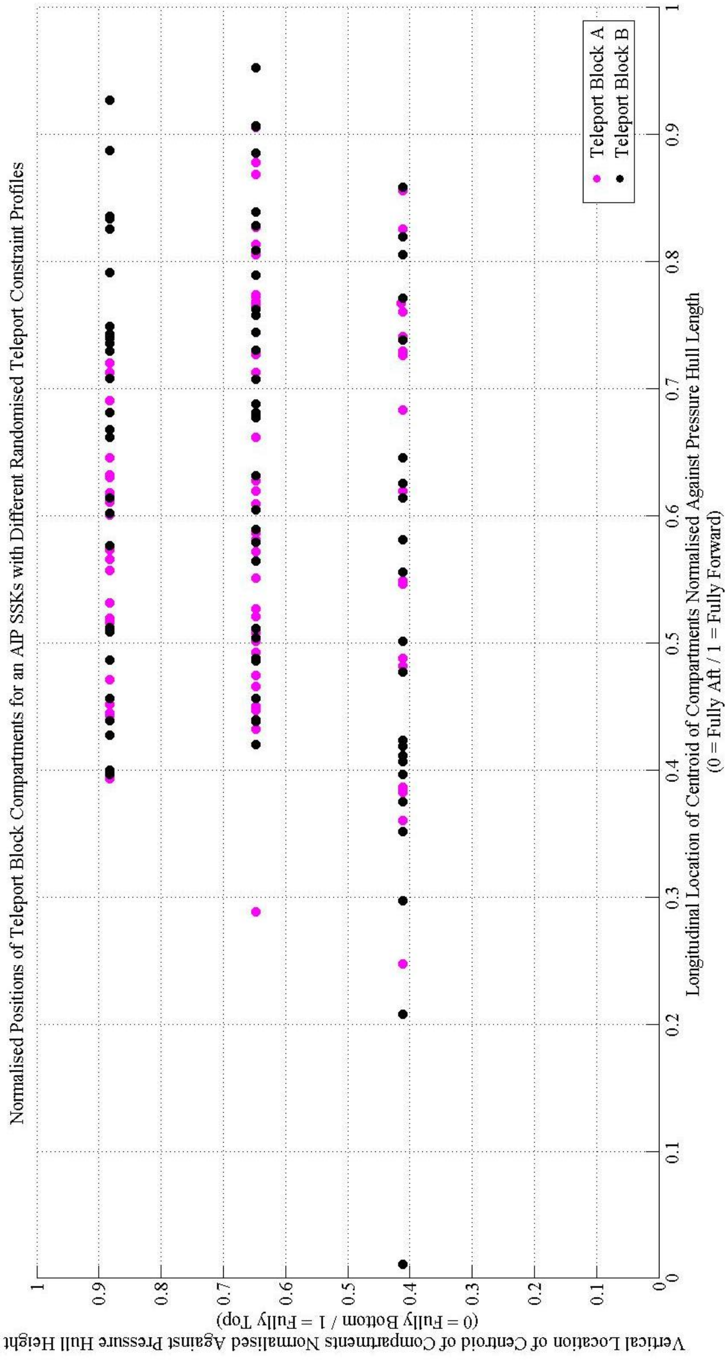

Figure 27 – Normalised Positions of Teleport Blocks for an SSK (AIP) with different Randomised Teleport Constraint Profiles

[1] The compartment centroids were normalised relative to the boat's PH length and diameter. A fully aft location has a longitudinal location value of 0 and fully forward is 1. Similarly, at the very bottom of the PH the vertical location value equals 0 and at the very top equals 1.

For the vertical location in the boat (y-axis in Figure 27), the centroid locations were discretised, since they had to lie on a given deck and the decks were assumed to run parallel and straight throughout the entire length of a pressure hull of the SST. Apart from allowing for large compartments, such as that containing the main motor, which could take up multiple decks. Figure 27 shows that there was not a pattern to be discerned between the vertical or longitudinal centroid locations of either of the ‘teleport blocks’. This was taken to verify that the ‘logistical effort’ part of the Compartment X-Listing routine in SUPERB could be appropriately modified to meet the demands of the investigated hypothetical experimental submarine concept.

5.3.3.iii Results

The normalised centroid locations relative to boat length and PH diameter for three major compartments from the 100 SST arrangements are plotted in Figure 28. The compartments selected belong to different functional groups in the arrangement. This was extracted from the 100 arrangements to ascertain whether there were any trends from the designs produced by SUPERB that were not specific to an arbitrary selection of certain compartments.

Unlike the plots of Compartments A and B in Figure 27, these plots for these three compartments do not reveal discretisation of the normalised vertical centroid locations that correspond to individual decks. This is because some compartments, such as the engine room, which could be spread across several decks and so the centroids of such compartments are to be taken to be at a height given by the centre of that compartment’s total height.

Figure 28 shows that, as predicted earlier in Subsection 5.3.1, the more dense engine room would be likely located both low down and away from the forward section of the PH[1], while the less dense Galley and C2 room would likely be located near the top of the pressure hull and more longitudinally diverse in their positioning. The effect of the randomised location relationships (explained in the previous subsection) from the ‘teleport block’ appeared to be pronounced, with no strong pattern for the relative longitudinal positions of any of the three example ‘normal’ components of Figure 28.

[1] The “less-constrained” set of Functional Constraints adopted for the SST investigation allowed for Independent Fully Electric Propulsion (IFEP) (see Hodge & Mattick (1997)). IFEP allows the propulsive power to be generated and transmitted by electrical cables to a motor. This removes the constraint applied to traditional submarine arrangement of the engine and (backup) motor aligned longitudinally to both power the propulsive shaft. Thus, the engine can be located anywhere in the boat.

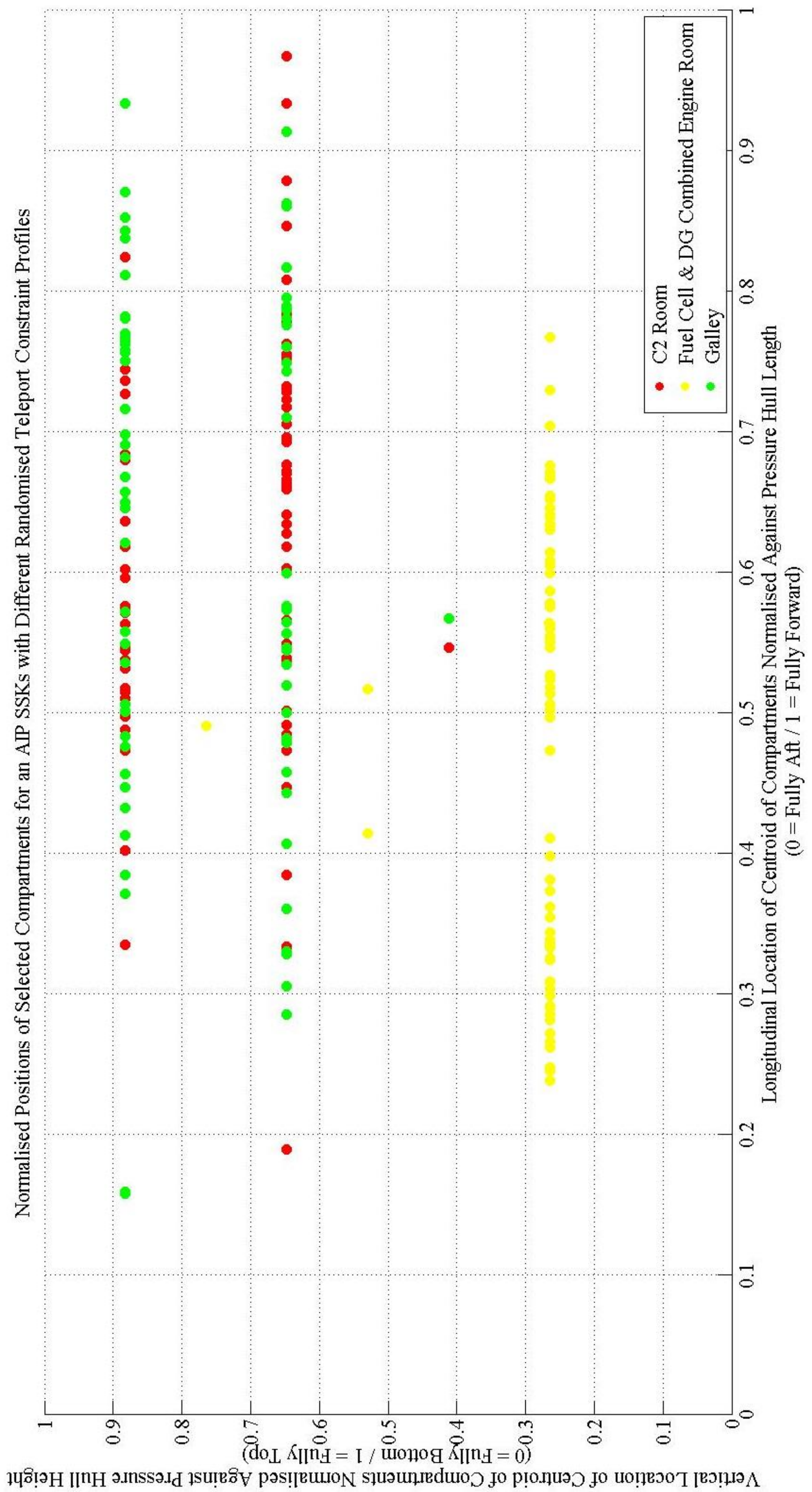

Figure 28 – Normalised Positions of Selected Compartments for an SSK (AIP) with different Randomised 'Teleport' Constraint Profiles

The SST ‘thought experiment’ indicates that the arrangement produced by Compartment X-Listing is dependent on compartment relationships and will not produce the same arrangement style for all submarines. The arrangement style (including any generation of unorthodox arrangements) appears to be strongly (but not exclusively) driven by setting up the ‘logistical effort’ Style Preference in Compartment X-Listing’s first Arrangement Step. It was therefore concluded that Compartment X-Listing is not simply a method that will reproduce the orthodox (conventional) arrangement style; especially if the sets of equipment and compartments are different from those likely to be fitted in current submarines. This, in turn, suggests that Compartment X-Listing is capable of producing a variety of arrangement styles – some of which could be unorthodox. To reiterate, the SST investigation is not intended to demonstrate that plausible unorthodox submarines could be produced. This is because that it is impossible to state with any confidence that any SST arrangements are plausible, given that the teleport technology is clearly hypothetical.

5.4 DEMONSTRATION OF SUPERB’S ABILITY TO GENERATE UNORTHODOX SUBMARINE DESIGN STUDIES

5.4.1 DEMONSTRATION INTRODUCTION

The previous section shows that SUPERB, using Compartment X-Listing, could generate arrangements that differ from orthodoxy and Section 5.2 suggests SUPERB could be used to consider designs with unorthodox equipment and physical features. To demonstrate that SUPERB could generate unusual designs with potentially unorthodox arrangements, the input to SUPERB was subsequently modified to recreate BMT’s SSGT concept design (BMT Defence Services, 2015). In this demonstration, close replication of the design was not of primary interest, but instead, an indication that SUPERB has sufficient flexibility to consider unusual designs, including those having unusual physical features. This was considered important in being able to populate the unrefined solution space when exploring potential SSH(N) options. The SSGT design incorporated an atmosphere-breathing Gas Turbine (GT), to be housed in a bulbous bridge fin, with ‘triangular’ casing to improve the hydrodynamic performance for near-surface transiting. The design of the SSGT also included a large portion of internal volume reserved for liquid oxygen (LOX) tanks used by a bank of fuel cells to facilitate AIP. This resulted in unorthodox arrangement features in the BMT design, such as all the auxiliary machinery being placed near amidships and on the Tankage Deck.

Principal Characteristics

Length overall	80.8m
Maximum beam	11.4m
Diameter of Pressure Hull	7.6m
Submerged Displacement [minimum, end of mission]	4,195t [3,570t]
Surfaced Displacement [minimum, end of mission]	3,700t [3,075t]
Complement	25

Mobility

- Maximum Sprint Speed [Submerged on Battery] — 30 knots
- High Speed Transit [Semi- Submerged on Gas Turbine(s)] — 20 knots
- Standard Transit [Snorting on Fuel Cells with reformed Kerosene] — 10 knots
- Maximum Continuous AIP Speed [Fuel Cells with reformed Kerosene/LOx] — 10 knots
- Maximum Transit Range: > 6,000 nmiles at 20 knots and 13,000 nmiles at 10 knots.
- Typical Mission – 2500nm transit out at 20 knots, 28 days AIP on task at 5 knots, return to base at 10 knots. Stores endurance 60 days.

Payload

- Radar, ESM and Extensive Communications
- Advanced Combat Management System – Conformal bow flank and fin arrays
- 6 x 21" torpedo tubes with 12 heavyweight or equivalent weapons
- 8 x VLS Tubes for heavyweight weapons
- Accommodation for 12 x Special Forces personnel
- 6 man Lock-in / Lock-out Chamber
- Provision for 40t/80m^3 of SF stores under casing and in pressure hull
- 4 x Large UUVs (some able to serve as SDVs)
- 16 x Countermeasures tubes

Figure 29 – Specifications for BMT's SSGT Concept Design (taken from (BMT Defence Services, 2014))

The SUPERB produced design solution used the ‘less-constrained’ set of Functional Constraints matching the one already presented in Table 14 as part of its Constraint Profile. However, the external arrangement tool (SEAP) was altered to follow closely the BMT arrangement. The Mathematical Modelling Module of SUPERB was also altered to take into account the bulbous bridge fin feature of the BMT design. The major design characteristics of BMT’s SSGT design are shown in Figure 29 and the design’s arrangement in Figure 30.

5.4.2 RECREATION OF THE BMT SSGT DESIGN USING SUPERB

The arrangement produced using the modified version of SUPERB is shown in Figure 31. The longitudinal position of the bridge fin in the study using SUPERB was considered an example of the limits of SUPERB’s auditing and analysis. In this case, the lack of a hydrodynamic assessment meant the process using SUPERB led to positioning the bridge fin further forward (which then agreed with the arrangement in the BMT design). Nevertheless, within the criteria set for naval architectural balance in Table 9 (see Subsection 4.6.1 on page 104), the SUPERB version could be assessed and this indicated that it was balanced to an early-stage concept level.

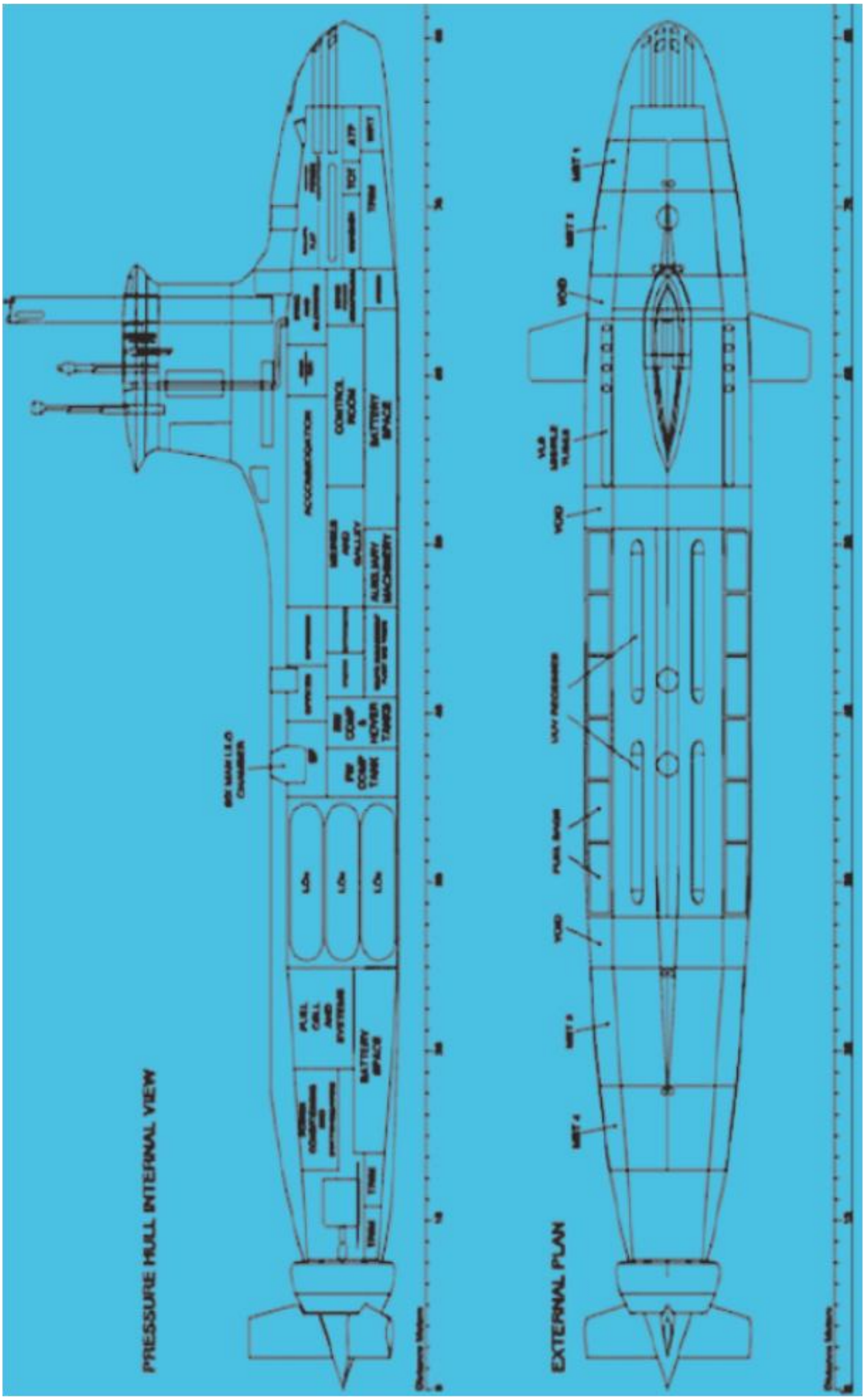

Figure 30 – Arrangement of BMT's SSGT Concept Design (taken from (BMT Defence Services, 2014))

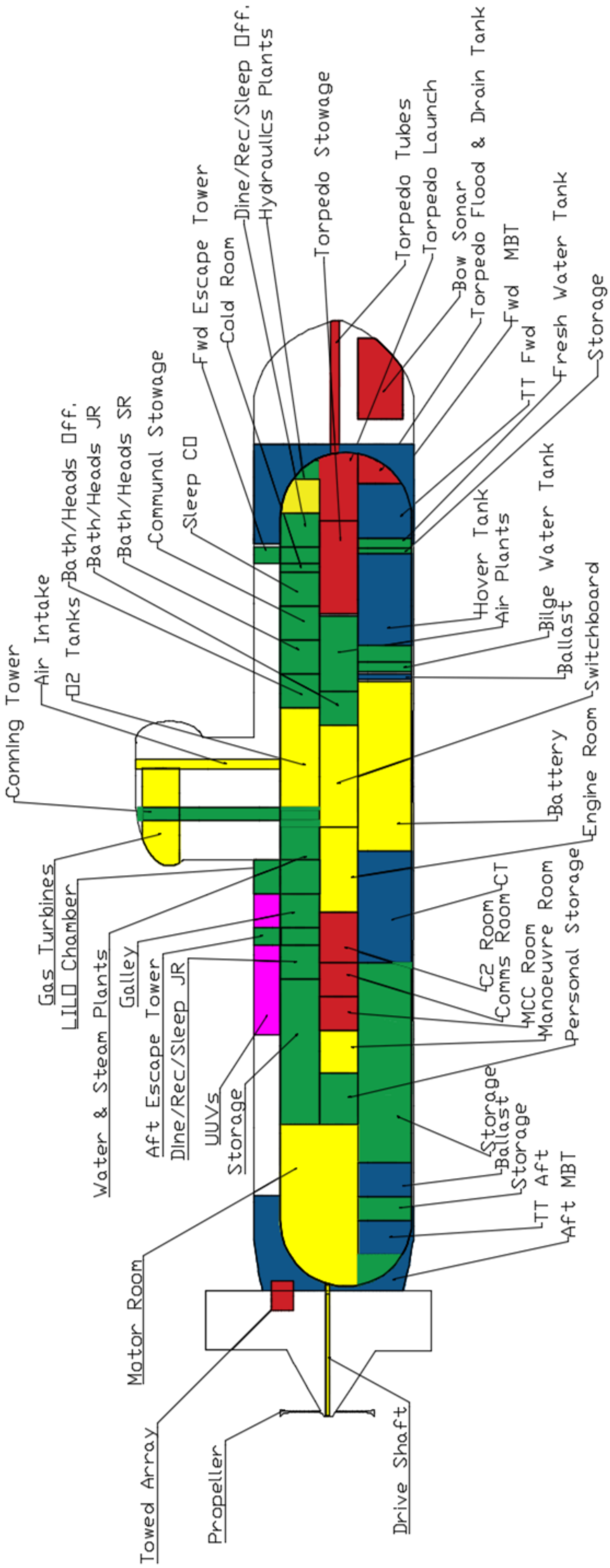

Figure 31 – Section View of SUPERB Produce Version of BMT's SSGT Concept

The modified Mathematical Modelling Module of SUPERB has 'interpreted' the design characteristics required to produce a submarine casing similar in shape that of BMT's design. A slight discrepancy arose in the SUPERB production of a pressure hull, due to the limitation of SUPERB's Mathematical Modelling Module in not being (currently) capable of considering pressure hulls with varying midsection diameters – such as the one used in BMT's design. SUPERB was unable to represent BMT's employment of differing deck heights and positions, which resulted in the BMT design having longer pressure hull end-sections. This also explains why the LOX tanks had to be placed on a single deck in the SUPERB produced version (see Figure 31).

The 'less restricted' Constraint Profile meant using SUPERB led to some radically different arrangement choices were made in comparison to those of the BMT design. For example, using SUPERB, the battery sets were combined into a single large compartment and placed approximately amidships to maintain hydrostatic balance. Another consequence of using SUPERB was that the Command and Control (C2) compartments were placed aft of amidships. This was due to the C2 compartments being switched in location with the LOX tanks, with the fuel cells being placed with the LOX tanks. The alterations to the Mathematical Modelling Module essentially enabled the recreation of the triangular casing adopted for BMT's SSGT design. It was considered that this demonstrated the flexibility in the use of SUPERB in that it could produce designs with unusual physical features. Thus, SUPERB was considered suitable to design unorthodox submarines with unusual features, such as UUV LARS, and thus is an appropriate tool to be used to populate the unrefined solution space of potential SSH(N)s.

5.5 CONCLUSION ON VALIDATION OF SUPERB

The validation of SUPERB was achieved by isolating and inspecting different components of the tool to build up a picture of its adaptability and to demonstrate its ability to consider concept designs with unusual physical features, while producing an arrangement that would be naval architecturally balanced. As a result of this validation of the SUPERB tool, and in particular, the Compartment X-Listing approach, confidence was given that it could fulfil the role of a 'generic' submarine design tool. It was further concluded that using SUPERB in the generation of submarine concepts could enable the defining of the bounds of a refined solution space through populating the unrefined solution space with potential designs. This approach for the production of the refined solution space is detailed in the next chapter and has been described as the Notional Pareto Front (NPF) approach.

CHAPTER 6 - THE NOTIONAL PARETO FRONT APPROACH

6.1 INTRODUCTION

This chapter outlines the NPF approach devised to produce the refined solution space using the SUPERB tool. It begins with the description and validation of a metric for assessing the performance of concept designs produced by SUPERB, the purpose of which is to reveal Pareto-dominated designs. Next, the difficulties of exploring the wide-ranging nature of the unrefined solution space and providing the motivation to develop the NPF approach are considered. The final section describes the proposed two-stage NPF approach. The first stage uses 'smart' sampling to define the region of unrefined solution space that potentially contains balanced and non Pareto-dominated designs following design synthesis. The second stage uses a control program to direct SUPERB to synthesise unrefined potential solutions (see Figure 14 in Subsection 4.2.2 on page 87) in order to identify a Pareto Front of naval architecturally balanced designs (at the concept level of design definition). These non-Pareto dominated designs could then be analysed to produce the refined solution space and thus, facilitate 'conventional' concept exploration.

6.2 THE MEASURE OF TRADABLE PERFORMANCE CHARACTERISTICS (MoTPC) AND COST

6.2.1 DESCRIPTION OF THE METRIC OF TRADABLE PERFORMANCE CHARACTERISTICS

A Measure of Performance (MOP) needed to be produced to determine non-Pareto dominated[1] designs. It has been was recognised that at the concept level of design, a true MOP cannot be reliably defined. While it was concluded from the review in Section 2.5 that arrangements should not be 'optimised' with an objective function (implying a metric), it was considered that some measure of tradable performance (the MoTPC) should be applied to an overall design in order to assess designs in decision-making.

The proposed MoTPC does not comprise 'true' measures of performance since some of the individual measures do not represent 'true' aspects of performance. Instead, MoTPC is comprised of proxies for some 'true' measures of performances. This approach is intended to overcome the difficulties with using a true MOP to evaluate concept level designs. For example, a true MOP would be associated with acoustic signature but

[1] Non-Pareto dominated in this instance means that there is not a submarine design option available (i.e. generated by SUPERB in the population of the unrefined solution space) with a higher assessed performance for the same cost.

without a detailed description of the submarine (well beyond the Concept Phase) and a comprehensive hydrodynamic analysis, it would be questionable to properly assess a design sufficiently at the concept level of definition.

Table 16 – Weightings for the Calculation of the MoTPC of a Submarine Concept Exploration

		Type of Tradable Performance Characteristic							
		Speed		**Skirmish**		**Survivability**		**Stealth**	
		Design Characteristic	**Weight**	**Design Characteristic**	**Weight**	**Design Characteristic**	**Weight**	**Design Characteristic**	**Weight**
System Group	**Strength**	Hull Hydrodynamics	0.33			Casing Stand-off Distance	0.20	Acoustic Signature	0.20
						RoB	0.20	DDD	0.20
	Nuclear Propulsion	Propeller Efficiency	0.33					Acoustic Signature	0.20
		Maximum Speed	0.22						
	Non-Nuclear Propulsion	Transit and Sprint Speeds	0.11					Indiscretion Ratio	0.20
						Emergency Escape on Batteries	0.20		
	Electronic Payload			Radar	0.07				
				Sonar	0.07				
				CMS & EW	0.07				
				Comms	0.07	Comms	0.20	Sonar	0.20
	Traditional Weapons Payload			ASuW & ASW	0.12				
				Mines	0.07				
				Land Attack	0.07				
				AAW	0.07				
				CM	0.04				
	UUV Payload			USGOT	0.33				
	Manning					Watch Keeping & Margin	0.20		
	Total Weight		**1.00**		**1.00**		**1.00**		**1.00**

The MoTPC is intended to identify which SUPERB generated designs are assessed as higher ‘performing’ at the concept level i.e. those which would be likely to lead to higher performing solutions once a design has been ‘fully worked up’ (using a true MOP). For example, the reserve of buoyancy (RoB) is not in itself an aspect of performance. However, it does indicate a level of survivability in a design (due to a design being able to withstand a small amount of localised flooding within the pressure hull). The taxonomy chosen for the proposed MoTPC is outlined Table 16. The values for MoTPC in Table 16 range from zero (no performance) to one (maximum performance score). A full description of the MoTPC calculation is provided in Appendix E. The MoTPC is an indicative metric used to show that the NPF approach can function as intended in differentiating between designs, in terms of perceived performance. Should the NPF approach described be used ‘for real’ to produce the refined solution space for a novel submarine concept exploration, it is considered that alternative metrics would need to be used to describe the required performance. These would need to take into account the peculiarities of the particular design problem and the available computational resources to undertake the associated design assessment.

6.2.2 VALIDATION STUDY FOR MEASURE OF TRADABLE PERFORMANCE CHARACTERISTICS (MoTPC)

The proposed MoTPC was subjected to an investigation to see that it is not solely a function of cost. Rather the MoTPC should be a representative measure that facilitates genuine design trade-off investigations. The study used a pool of approximately 10,000 (unrefined) submarine designs randomly generated by SUPERB, in order to achieve the objective stated in Subsection 2.7.1 of devising a suitable performance metric. The results of this study have been plotted in Figure 32. The designs were intended to cover the unrefined solution space produced using SUPERB’s Mathematical Modelling Module (as detailed by Table D1 in Appendix D Section D.2). This included regions of the unrefined solution space seen to be occupied by unorthodox designs. The Pareto Front in Figure 32 (red line) is an unrefined Pareto Front – meaning the solutions on this front are not yet verified to be naval architecturally balanced as a proper design synthesis has not yet been performed.

The values for the MoTPC shown in Figure 32 do not span the full range of MoTPC values (zero to one), as the improvement of one type of performance, such as speed, is traded off against another type of performance, such as stealth. For instance, a more powerful power plant for propulsion of a submarine design (with all other things being equal) resulted in a design that emits a greater amount of acoustic energy and hence has increased signatures. It was concluded that this indicates that the MoTPC reflects design trade-offs, as it was intended to do. The lack of a statistically significant correlation between cost and MoTPC in Figure 32 was taken to be as evidence that the performance of a SUPERB-generated design is not a simple (linear) function of the size and hence cost.

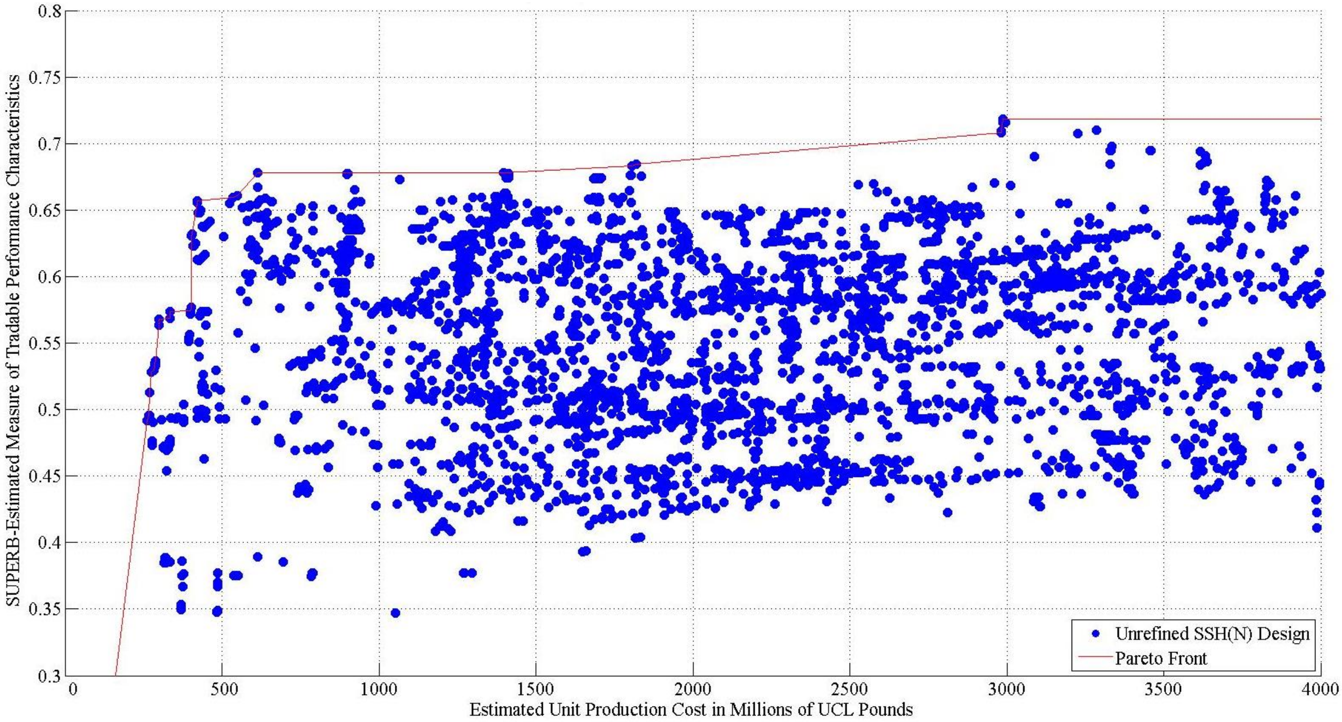

Figure 32 – Study of SUPERB-Generated Designs for MoTPC versus Cost

To remove any doubt that both the cost and the MoTPC are only parametric functions of the size of the vessels generated by SUPERB, Figure 32 has been recreated in Figure 33, with the submerged displacement also considered. Submerged displacement was chosen as the investigated characteristic as it was considered that if any design characteristic had complete influence on MoTPC and cost, submerged displacement would be the most likely.

There is an approximate trend in Figure 33 with larger vessels having a higher assessed performance and a high cost. Vessels with a greater displacement can typically accommodate a greater amount of equipment (which is responsible for a portion of the overall performance) than smaller vessels. However, the inclusion of a larger amount of equipment also typically necessitates a higher cost. However, Figure 33 also shows that for equally sized submarines, the performance (MoTPC) calculated by SUPERB can vary greatly, typically with MoTPC (overall) values of between 35% and 70%. This was taken to indicate that other characteristics being traded-off in the design are having a significant effect on the overall value for the MoTPC and not just the size of the vessel. Some nominal designs in Figure 33 have the same size and performance but different assessed cost. This is because there are multiple ways to which a specific overall performance value could be arrived at when using the MoTPC metrics, due to differing design characteristics. The corollary is that a SUPERB-generated submarine design's MoTPC metrics and cost are not just a function of its overall size. The MoTPC was thus considered a suitable metric for use in investigating design trade-offs for submarine concept designs, and thus could be used to populate the unrefined solution space with potential designs using SUPERB.

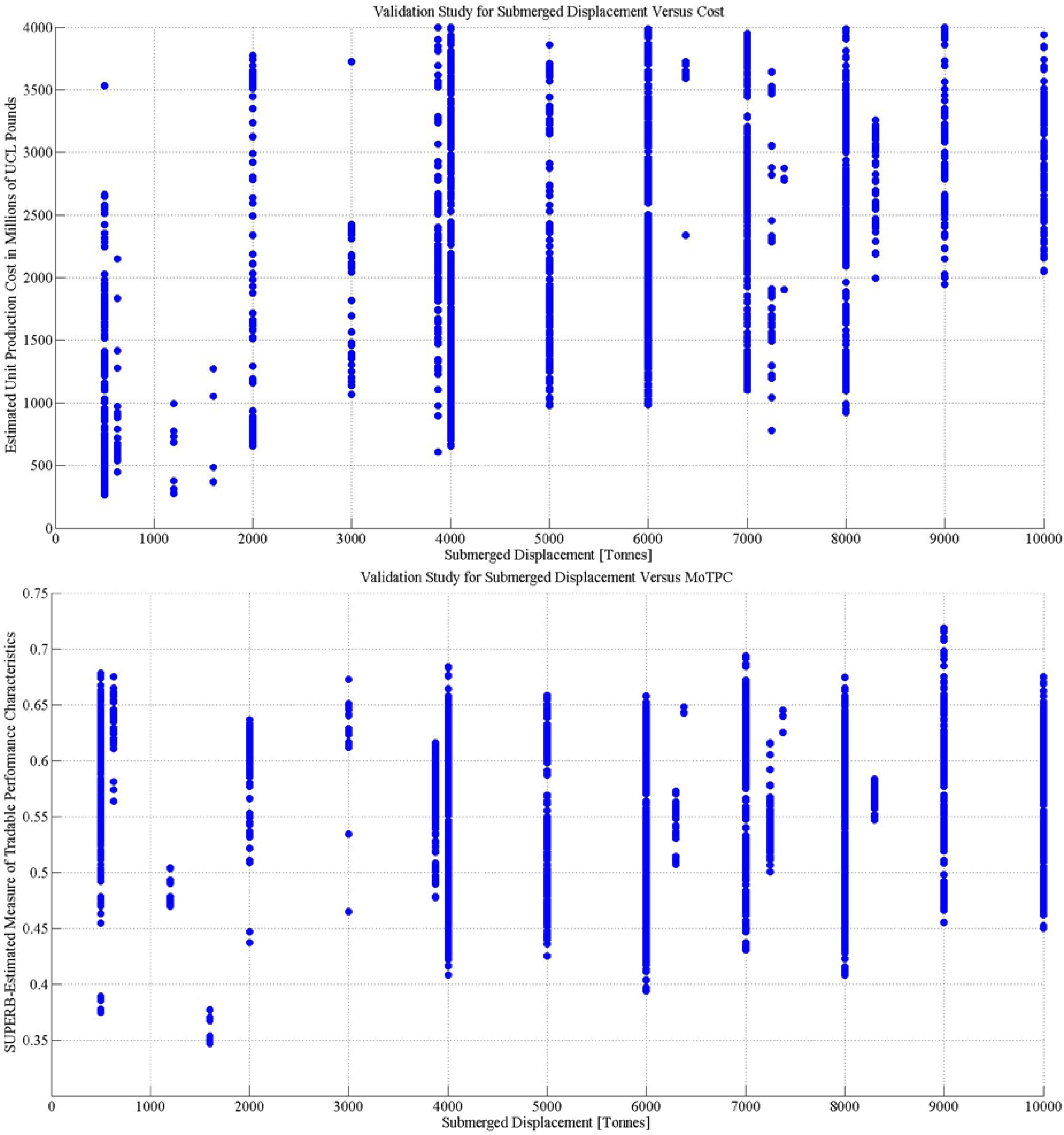

Figure 33 – Study into the Effect of Submarine Displacement on Cost and MoTPC of SUPERB-Generated Designs

6.2.3 DESCRIPTION OF THE COST METRIC

The cost of a SUPERB-generated submarine design is calculated on the Unit Production Cost (UPC) basis. This is inconsistent with the UCL's Submarine Design Procedure (NAME Office, University College London, 2012c). The data for costing was taken from the UCL Submarine Design Databook (NAME Office, University College London, 2012b), which lists the cost at 2008 prices, in millions of 'UCL pounds' per tonne of each weight group. This produces a cost value in UCL pounds, which is considered believable, but not necessarily wholly accurate when compared to likely cost outcomes for real submarines. This scheme has been adopted in lieu of using reliable data, as much is classified or commercially sensitive. This estimated costing scheme should only be used to distinguish between design alternatives in the Concept Phase of design and not to make final design selections, as the fidelity of the cost analysis would not be sufficiently high. The cost metric was considered acceptable for use with SUPERB to indicate only the degree to which submarine design studies are likely to be expensive or cheap, once they have been fully 'worked up'. A summary of the cost calculation process is included in Appendix D Section D.5.

6.3 THE MOTIVATION FOR ADOPTING THE NOTIONAL PARETO FRONT APPROACH

6.3.1 INTRODUCTION

The 'generic' design tool (SUPERB) has been validated, facilitating the development of an approach (proposed in Section 2.6) to produce a refined solution space and thus meet the objectives set out in Subsection 2.7.2. This approach is called the Notional Pareto Front (NPF) approach. It was concluded in Section 2.3 that the NPF approach should be capable of defining the bounds of the refined solution space within a practical timeframe. It was suggested that this timeframe should be in the order of a few weeks. It was considered that this timeframe, should it be used further for a research investigation, would enable a large amount of computation to be undertaken and sufficient design data to be collected without overly constraining the rest of the concept design process.

6.3.2 THE DIFFICULTY WITH SIMULATING 'EVERY' DESIGN IN THE UNREFINED SOLUTION SPACE

The number of unique designs in the unrefined solution space is essentially unquantifiable, due to the endless list of equipment that could be incorporated into a vessel's design, and some of the design characteristics being continuous in nature (e.g. the maximum speed). As a result, it is impossible to consider *every* design in the unrefined solution space.

It was considered that 'every' conceivable concept design in the unrefined solution space could be represented by using combinations of values of the circa 30 top level input variables used by SUPERB, such as Deep Diving Depth (DDD) and submerged displacement, to generate designs using its Mathematical Modelling Module. These values could be a few (typically five to seven) discrete possible values to approximately represent a wide range of possible values. It was considered that this was an acceptable simplification, since at this stage of the design process designs still lack considerable design fidelity, and thus 'fine tuning' of the exact values could be performed subsequently (as has been discussed in Section 2.3). A typical set of ranges for the input variable values used in the Mathematical Modelling Module of SUPERB is provided in Table D1 in Appendix D Section D.2.

It was considered there would be two drawbacks to an approach that considers an excessive number of combinations of the top-level input variable values. Firstly, the amount of computer memory required to store the results dataset (as a matrix) would be very large. Approximately 30 top-level input variables are used by SUPERB to generate a typical SSH(N) concept and generally, and five to seven values are specified for each input variable – thus a matrix of five to the power of 30 (equal to 9.31×10^{20}) elements would be required to store the results. If ten bytes were assumed for each data point, 7.88 zettabytes of storage would be required (7.8 times the predicted information of the entire internet for 2015 (Hesseldahl, 2011)). Clearly, this would be impractical. The second drawback would be the computation time. Assuming one minute per design using a standard modern personal computer[1], the time to calculate all the designs would take 1.77×10^{15} years or 110,000 times the age of the universe.

6.3.3 THE TECHNICAL SOLUTIONS TO SIMULATING 'EVERY' DESIGN IN THE UNREFINED SOLUTION SPACE

It was concluded that the population of the full range of potential designs should be sampled in the unrefined solution space for a given SSH(N) investigation. It was considered that populating the unrefined solution space could still be performed using sampling, but this could also be undertaken in a practical period. Slovin's formula

[1] A typical personal computer constructed circa 2012.

(see (Altares, et al., 2003)) was used to identify an acceptable size of the required sample population for such a range of designs by calculating a statistical level of confidence (90%). The level of confidence was chosen as a way to measure confidence in the identification of underlying trends for non-Pareto dominance.

The assumption of random selection was assumed gave a one-tailed confidence interval with randomness modelled using a normal distribution. This it because it is only of relevance if the subset of sampled designs have not been sampled by chance, while the two-tail confidence probability of the said performance is only at either extreme, i.e. either high or low. The applicability of Slovin's formula (i.e. normal distributions) to the NPF approach is discussed later in Subsection 8.3.5.

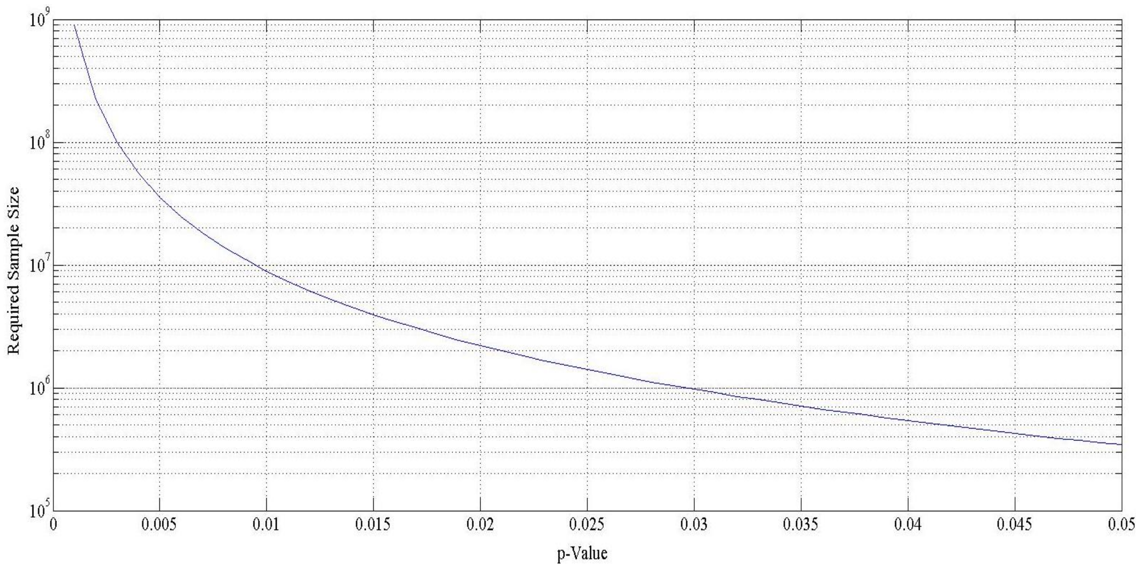

Figure 34 – Sample Size Population for the Full Range of Potential Designs in the Unrefined Solution Space using Slovin's Formula (Altares, et al., 2003)[1]

If SUPERB could generate 300,000 unique unrefined potential solutions (assuming one minute per design and 25 modern day CPUs[2] running in parallel for 9.1 days), then a p-value[3] of about 0.05 could be expected (see Figure 34) – corresponding to a confidence level of 90%. It was considered that this provides a satisfactory trade-off between computation time and confidence to represent the unrefined solution space using sampling. SUPERB takes approximately one minute to generate the equipment and compartments of a concept design

[1] Figure generated by the candidate. The total population size is the 300,000 unique potential solutions.
[2] Typically 2.0 GHz.
[3] A p-value of 0.05 is a typically used value in statistical analysis to describe confidence. See isixsigma.com (2015) for further explanation.

using the mathematical modelling module. It typically takes 30 to 60 minutes for SUPERB to generate a synthesised concept design (i.e. the complete SUPERB process), including an arrangement. Clearly, it would be impractical to generate 300,000 synthesised concept designs, as using the same 25 personal computer CPUs already invoked this would take an estimated 526 days.

It was considered that increases in computational power should rapidly reduce the computation time. For example, using Moore's law (Moore, 1975) as a 'rough guide' to predict CPU speed, in around 12 years' time (2028) the computation required to generate the 300,000 unique unrefined potential solutions may be achievable within 3.55 days on a single CPU (assuming also similar cost to its 2015 ancestor). On a similar basis, to generate all 300,000 synthesised designs it might take 205 days on one CPU. Indeed, it is estimated that if Moore's law is still applicable, it will take until 2042 (27 years' time) for it be possible to generate 300,000 synthesised designs on a single CPU within 24 hours. It was thus concluded that it is not yet computationally practical to generate a very large pool of synthesised concept designs and subsequently analyse them. However, approach devised to currently produce the refined solution space should be capable of considering and handling approximately 300,000 unique unrefined submarine designs and be capable of using SUPERB to synthesise a lesser number of them. The approach should be capable of 'smartly' identifying and selecting which of the unrefined potential solutions to spend relatively expensive computation time to synthesise to a balanced level, using SUPERB. This 'smart' selection was thus considered part of producing the refined solution space.

It was considered that the high computation levels needed to sample the unrefined solution space justified the use of highly automated computer-based approach and associated tools to perform both the generation of submarine designs and the production of the refined solution space. It was further considered that any substantial direct human interaction would result in the length of time to populate the unrefined solution space – and hence the overall submarine concept design exploration process – becoming impractically long.

It was also considered that another implication of synthesising 300,000 potentially balanced designs would be the amount of computer memory needed to work simultaneously on multiple designs. If one megabyte were needed to store a SUPERB-generated balanced design, then approximately 300 gigabytes of RAM would be needed to work on all the designs simultaneously.

There could also be potential RAM difficulties should all the designs be loaded simultaneously into a computer program. The solution devised for this problem was to load/unload the designs into the computer program dynamically, as and when they are required. It has been noted (Walter, 2005) that in the near future expected improvements in the level of memory built into PCs should remove this need for dynamic loading.

The next section describes the approach devised to perform to produce the refined solution space using SUPERB to populate the unrefined solution space, namely, the Notional Pareto Front (NPF) approach.

6.4 DESCRIPTION OF THE NOTIONAL PARETO FRONT

6.4.1 TOP LEVEL DESCRIPTION OF THE NOTIONAL PARETO FRONT

The proposed NPF approach generates and modifies a Pareto Front for a plot of submarine cost versus some measure of performance (i.e. MoTPC).[1] This top-down approach is intended to reduce the required memory storage for the results dataset and to reduce the simulation times, should it be used 'in anger' for the investigation of novel concepts, such as the SSH(N).

The central premise of the NPF approach is to define the refined solution space. It is a two-step process. Firstly, a large portion of the unrefined solution space is removed before the synthesis of (potentially) balanced designs is undertaken (using SUPERB). This unrefined solution space consists of potential designs (i.e. nominal solutions created using only the Mathematical Modelling Module of SUPERB) that if synthesised, would produce naval architecturally unbalanced concept designs or concept designs that were clearly Pareto-dominated by other balanced concept designs. This step is called 'smart' sampling as the samples selected are considered unrefined potential solutions that could conceivably produce balanced and non Pareto-dominated concept designs. The result of this intelligent sampling is a pool of unrefined but conceivable designs, such as the one shown in Figure 35.

The second step in the NPF approach is the top-down determination of the "Balanced Pareto Front", using the set of designs provided by the first step in the NPF approach. The Balanced Pareto Front (BPF) contains naval architecturally balanced concept designs produced from those taken from the pool of unrefined conceivable

[1] In this example, the potential designs are benchmarked to scale linearly relative to a Basic Submarine Design. A value of 100% equates to twice the cost/performance of the Basic Submarine Design. The Basic Submarine Design has been outlined in Table D2 in Appendix D Section D.3. It is intended for the NPF to be easily generated by ensuring all the cost and performance values of these potential designs were greater than that of the Basic Submarine Design.

options. The Balanced Pareto Front could then be used to define the refined solution space, and hence, facilitate 'conventional' concept exploration.

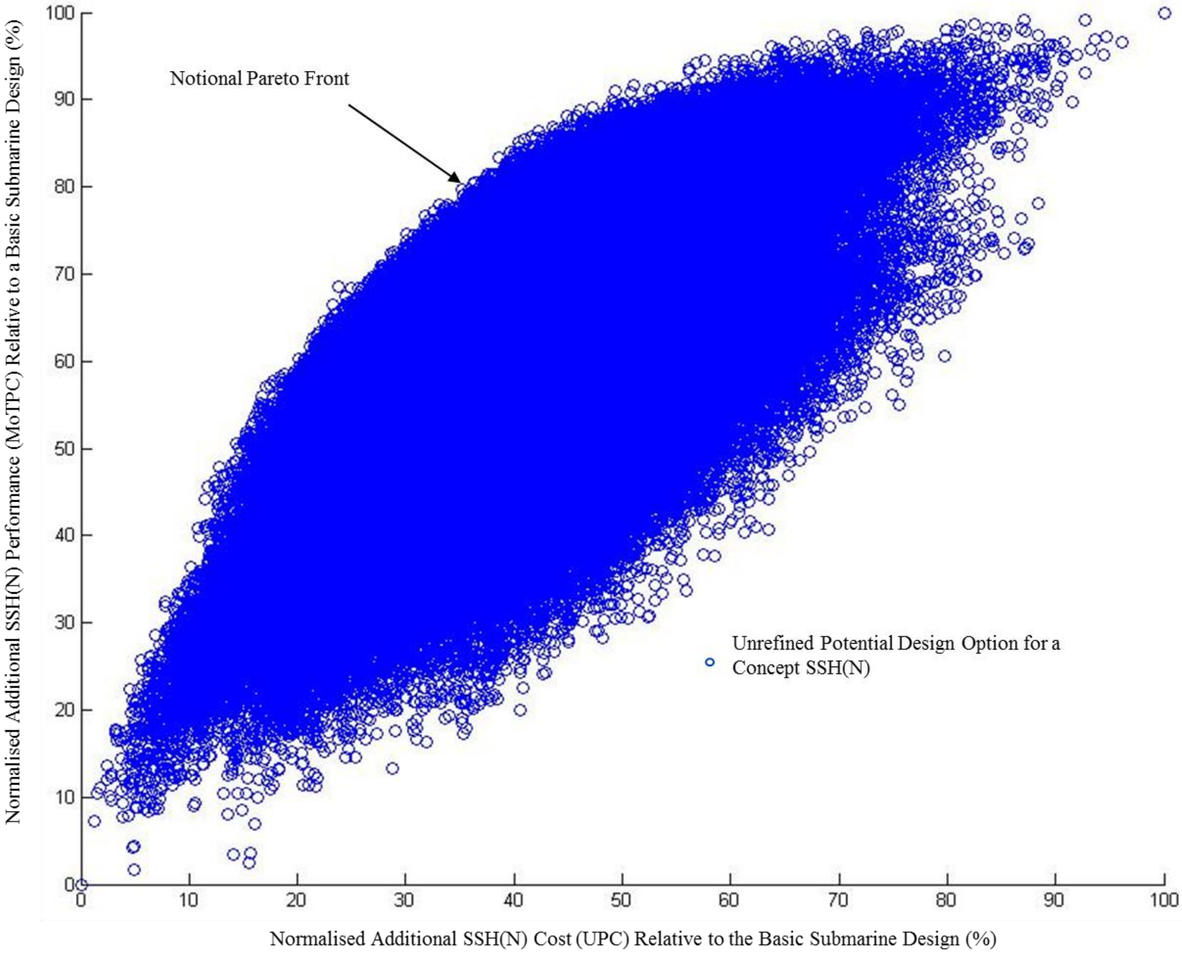

Figure 35 – Results of a Monte Carlo Simulation to Generate the Pool of 300,000 Conceivable SSH(N) Design Options

6.4.2 'SMART' SAMPLING

In order to produce the 'smart' sampling of the unrefined potential solutions, it was considered that an approach should be devised, which could obtain results in a practical timeframe, being in the order of days. The devised 'smart' sampling approach entails the subdivision of the components of a nominal design into major systems groups (SGs) where each SG can be generated using a few specific top-level input variables in the Mathematical Modelling Module of SUPERB. A set of individual systems (e.g. a motor) comprise a system group (e.g. propulsion). An illustrative example of this breakdown is given in Eqn. 9.

$$SG_{Propulsion}=f(Power_{DG}, Power_{RC}, \eta_{Propulsor}, Num_{ST}, Num_{TG}, etc\ldots)^{1} \qquad \text{[Eqn. 9]}$$

An example of the SGs and the distribution of top-level input variables are shown in Table D1 in Appendix D Section D.1. SGs have been used as it was considered that they reduce the extent of computation needed to generate the pool of potential submarine options, such as those shown in Figure 35.

Each design option can be generated from a set of randomly selected system group options (e.g. a selected propulsion type) and each system group option is considered to be on a Pareto Front for its system group type. This is to ensure that each selected system group option is non-dominated by another system group option. This is ultimately intended to ensure that potential designs with Pareto-dominated SG options are not sampled – thus making efficient use of computational resources. The random selection is a Monte Carlo simulation of designs in the unrefined solution space, which is effectively focussed by the 'smart' sampling using system group-level Pareto Fronts. It was considered that the approach is suitable for the generation of potential submarine design solutions, if each individual SG-level Pareto Front is comprised of feasible options (at the SG-level) for that system group. The models should be inspected in the Mathematical Modelling Module of SUPERB to ensure that they generated feasible SG options. The synthesised submarine designs on the subsequent Balanced Pareto Front should thus be both feasible and comprised non-dominated system group options.

The definition of a system group effectively helps define a boundary of the refined solution space, thus separating out which of the SG options can be assessed (before any design synthesis) as being feasible, or not. A trivial example of this SG-level bounding would be the drilling of a hole in a rectangular steel plate. If the hole could be imagined as a 'system group' and the overall plate as a synthesised design – it is readily known that the hole must have a diameter greater than zero and no greater than the width of the plate. It is not readily known what the optimum diameter might be, but some infeasible diameters could be discarded. This definition of feasibility facilitates the 'smart' sampling step in the NPF approach. It was considered that at the SG-level, there was sufficient knowledge (at the concept level of definition) for the system groups that comprise an SSH(N) to define the feasibility of system group options, within a practical timeframe. It was considered that SG-level Pareto Fronts should ensure that feasible SG options are used in generating the unrefined SSH(N)

[1] $Power_{DG}$ = Combined power of the diesel generators; $Power_{RC}$ = Combined power of the nuclear reactor(s); $\eta_{Propulsor}$ = Combined efficiency of the propulsor; Num_{ST} = Number of steam turbines; Num_{TG} = Number of turbine generators.

concept designs, and minimise the amount of 'smartly' sampled unrefined potential solutions, which would not lead to naval architecturally balanced concept design following synthesis using SUPERB. A corollary of 'smart' sampling is that the less available knowledge about a system group, the less 'smart' the sampling and thus, the greater the probability that sampled unrefined potential solutions could lead to unbalanced designs following synthesis. Thus, by incorporating a novel technology, such as UUVs, the associated payload system could be expected to be a more probable cause of synthesised designs turning out to be unbalanced.

In theory, it was considered that the SGs could consist of any combination of top-level input variables for this approach to work. However, there was seen to be an advantage in grouping complementary top-level input variables together as recognisable 'genuine' submarine systems. A 'genuine' system group, such as propulsion, could have values that could be compared to existing data (and designer experience) from existing submarine designs. Each SG produces its own cost versus measure of contribution to the whole–boat level performance Pareto Front. The whole boat performance measure is used instead of the SG performance, to avoid SG-level Pareto Fronts comprising of systems which when the whole boat is synthesised, cannot produce a naval architecturally balanced submarine design. If a disparate or poorly structured set of top-level input variables were used to create a 'synthetic' (i.e. not 'genuine') SG, any validation through designer inspection and comparison with other SG Pareto Fronts would be far more difficult. The number of top-level input variables per SG has been rationalised in an effort to minimise the amount of computation required to generate the SG-level Pareto Fronts. This 'optimisation' has been described in Appendix D Section D.3.

6.4.3 DETERMINING THE BALANCED PARETO FRONT

6.4.3.i Description

The pool of unrefined but conceivable designs (shown in Figure 35) establishes an NPF of unrefined submarine designs (i.e. unsynthesised and thus still in the unrefined solution space). These are expected to be close to a Pareto Front of naval architecturally balanced submarine designs (the Balanced Pareto Front (BPF)), given it is generated from a pool of unrefined submarine options using 'smart' sampling. For a given cost point, the approach is then to search for the non-dominated balanced design, using a control program starting with the unrefined potential solution at the NPF and working down though unrefined potential solutions until a balance solution enables the Balanced Pareto Front to be formed. This process is illustrated in Figure 36.

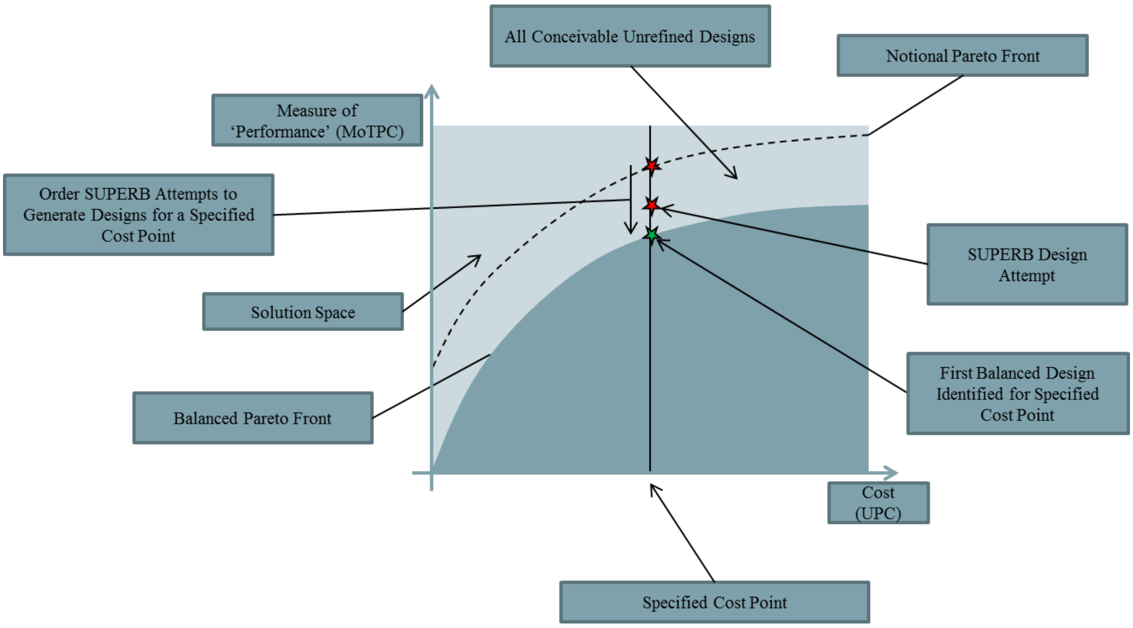

Figure 36 – Illustration of the Control Program Instructing SUPERB Using the Notional Pareto Front to Locate the Balanced Pareto Front

This top-down approach is intended to ensure that SUPERB only needs to synthesise relatively few designs, during the investigation of concept designs such as SSH(N)s. The approach of using Pareto Fronts is intended to ensure that SUPERB is only supplied with values of top-level input variables, to produce refined submarine designs that are close to the 'actual' Balanced Pareto Front representing whole-boat performance versus cost. Genetic Algorithms, such as those employed by Daniels et al. (2009) and van Oers (2011), offer an alternative approach to using NPF to determining balanced submarine concepts lying on a Pareto Front. They have been discussed in Subsection 2.5.3. However, it was considered that a level of mutation required to explore the unrefined solution space sufficiently would require a low level of elitism[1] when successive generations of designs were evolved. It was considered that this would also require a high number of generic algorithm generations to be employed and, potentially, a higher computation load would be required to identify a (naval architecturally) Balanced Pareto Front.

6.4.3.ii The Control Program Determining the Balanced Pareto Front

The control program works by taking the pool of potential submarine design options and sub-dividing this pool into 'columns'. Each of these columns is centred on a specific cost point and has a width of ± 0.1% of the UPC

[1] Elitism the favouring of a certain design aspect when a genetic algorithm generates subsequent 'generations' (i.e. sets of designs).

on a continuum between the lowest and highest costing potential submarine design options. The control program instructs SUPERB to select the design option with the highest performance (MoTPC) for a specified cost point. The control program then progressively works down a 'column' for all design options with the same cost, until it selects a design that it shows to be balanced. The latter is then the non-dominated design option for that cost point, which is then plotted on the Balanced Pareto Front. A broad outline of the process governing the control program is outlined in Figure 36. The number and value of the specific cost points of interest are selected by the designer and inputted into the control program to enable the creation of the BPF. In a test of the NPF approach (which is described in the next chapter), 81 evenly spaced specific cost points were investigated using the control program. They ranged from 0% to 100% UPC and spaced every 1.25% of UPC on the cost continuum.

6.4.4 LEVEL OF ACCURACY

SSH(N) designs of potential interest, for example, such as those on any 'knee of the curve' on the Balanced Pareto Front (i.e. the range of submarine designs which are likely to represent the 'best value for money'), could be subsequently recreated in Paramarine. These could then be inspected and independently audited, using Paramarine's more extensive assessment tools where appropriate to the level of design granularity produced at this design stage. This would give greater assurance that these designs are sufficiently balanced submarine concept designs. Following the investigation of any concept, such as SSH(N)s, such a check would confirm that SUPERB has reasonably represented any novel submarine concept, to a concept level of definition.

6.4.5 HOW DESIGN TRENDS MIGHT BE IDENTIFIED

A statistical analysis of submarine designs could be undertaken to uncover trends from the designs on the Balanced Pareto Front. The analysis could be a focused investigation of the set of designs lying close to the 'knee of the curve'. A statistical investigation of the modal analysis of the values of top-level input variables, for the submarine concept designs that lie in the range of the 'knee of the curve', might reveal statistically confident selection trends. This, in turn, could indicate the characteristics of a potential preferred SSH(N) concept design, including preferred stylistic selections, which could be analysed to discern preferred styles.

For these reasons an analysis of a set of balanced designs is considered to be advantageous over simply selecting the single SSH(N) design, which apparently gives the best 'value for money' trade-off on the Balanced Pareto Front. Firstly, the large margin of error associated with concept levels of definition means a point design selected as the apparent best value for money (the ‘knee on the curve’) may not be once it is worked up in detail. However, it was considered that by analysing a range of apparently best value for money designs, a degree of confidence could be obtained into the identification of an optimal region (as defined by the ‘knee in the curve’) in the refined solution space. Secondly, if only one design is used to base conclusions on the ‘optimal’ SSH(N) concept design, all future work on developing subsequent SSH(N) designs might be driven by the peculiarities of that design. Some of these peculiarities may lead to a design which could well be near the ‘edge of the cliff’ in terms of cost versus performance. Variations in the technical solutions and resultant cost, due to margins of error at concept level of definition, could make the design unstable or unaffordable. Rather an analysis of a range of submarine designs could provide insight into the ‘optimal’ region of the refined solution space, ensuring that the apparently best value for money design is robust against drastic changes emerging during the subsequent design development, which in turn, should increase confidence in any observed design trends.

6.5 CONCLUSION

This chapter has described a metric (MoTPC) which has been used with SUPERB to assess a synthesised design’s performance. The two-stage NPF approach has been described as the solution to the research proposal put forward in Section 2.6. The principle guiding the NPF approach is that the unrefined solution space should be reduced by removing regions that are considered not to be of interest in producing of the refined solution space (using ‘smart’ sampling). This is intended to ensure the time required for computation remains practical (i.e. a few weeks). The (reduced) unrefined solution space could then be used to generate the BPF of naval architecturally balanced designs from which concept exploration could be subsequently undertaken. It is necessary to verify that the NPF approach performs as intended. This is covered in the next chapter.

CHAPTER 7 - TRIAL EXECUTING THE NOTIONAL FRONT APPROACH

7.1 PREPARING THE TEST OF THE NOTIONAL PARETO FRONT APPROACH

7.1.1 THE SETUP

This chapter considers the two steps of the NPF approach described in the previous chapter, to see if they functioned as intended. The NPF approach was tested to see if it could produce the refined solution space using SUPERB for the exploration of SSH(N)s. It was intended that by testing the NPF approach, theoretical issues and practicalities could emerge.

The Mathematical Modelling Module of SUPERB was used to generate equipment and compartments at the concept level of granularity[1] for each of the seven System Groups (SGs) so that each SG-level Pareto Front could be generated using the 'smart' sampling approach described in Subsection 6.4.2. For expediency, in testing the second stage of the trial of the NPF approach, proxy models were created to represent crudely each SG-level Pareto Front generated from the relevant 'actual' mathematical models for each SG. The proxy models of each SG-level Pareto front represent their approximate contribution to the overall submarine cost and 'performance' using its top-level input variable values. This then avoided not performing the computationally expensive task of describing equipment and compartments when options were compared against each other. It was considered that the relative values of the proxy model for cost and performance were deemed to be important, rather than the absolute values. This was done for each type of SG. Options from the (proxy model) SGs were then combined to rapidly generate a 'believable' pool of SSH(N) options, from which the viability of the NPF approach could be tested. The generation time for these options was reduced from a few weeks for the 'actual' solutions to a few hours for the 'proxy' solutions, which are shown in Figure 35 in Subsection 6.4.1 on page 142.

For comparison, Figure 37 presents a comparison between the 'actual' and proxy models for the Manning SG-level Pareto Front by plotting each non-Pareto dominated SG option. Figure 37 shows an

[1] This is the equipment and compartments modelled in Appendix E.

approximate representation of the 'actual' Manning SG-level Pareto Front, indicating that the adoption of proxy models in 'smart' sampling during the test is appropriate. The 'step' between cheaper and poorer performing Manning SG options can be seen for both the proxy and real models. This represents the change from a two watches/day to three watches/day system. The copying of this feature by the proxy model suggests the adoption of proxy models were appropriate.

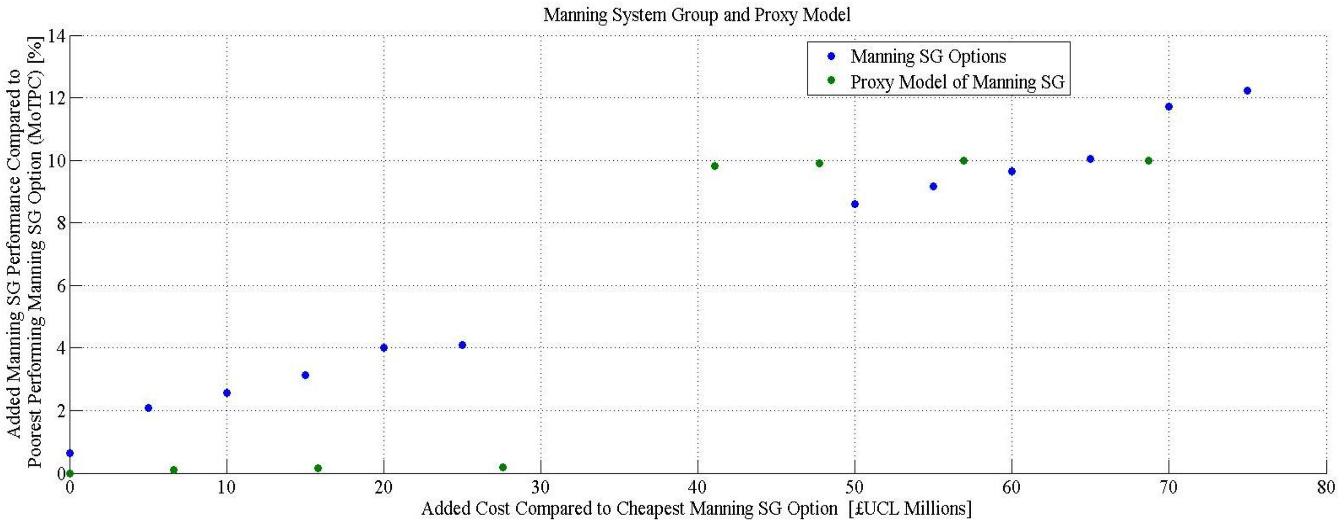

Figure 37 – Comparison of the Manning SG and its Proxy Model[1]

It was considered a sensible approach to test if proxy models were sufficient to substitute for those mathematical modelling sections in SUPERB describing the 'performance' and cost of SGs, and so check the NPF approach. Should the approach be executed 'in anger', then proxy models would not be appropriate, as they are not actually describing individual equipment items and compartments. Thus, there would be an insufficient level of detail to determine reliably non-Pareto dominated potential designs and hence, generate a reliable NPF.

7.1.2 THE ISSUE OF THE SEQUENCE OF SYSTEM-LEVEL PARETO FRONTS

A design option contained within the pool of conceivable and yet unrefined SSH(N) concept designs (illustrated in Figure 35 on page 142) comprised a selection of System Group (SG) options taken from

[1] The measure of 'performance' (MoTPC) and cost (UPC) in the figure is the contribution of the Manning System Group to the overall boat's 'performance'. Thus, since there are seven SGs, a rough upper limit for the 'performance' contribution could be expected to be around 1/7 of 100% i.e. ~14%.

a series of SG-level Pareto Fronts, as per the description of ‘smart’ sampling in Subsection 6.4.2. The SG-level Pareto Fronts had to be generated before they could be used to provide the source of SG options contributing to a specific potential design option. The sequence in which the pre-calculated SG-level Pareto Fronts were generated was seen to be important in minimising the extent of computation in undertaking this testing of the NPF approach and is thus discussed at this juncture.

Each System Group (SG) option was mathematically modelled by a small (typically six) set of top-level input variables using SUPERB’s Mathematical Modelling Module. It was considered that each top-level input variable should only be assigned a single value for the generation of a limited set of equipment items and physical features that comprise a submarine design appropriate to a concept level design. This was to ensure that a design was consistent. This avoided producing a design which called for a propulsion system solution based on one transit speed and ship stores calculated for a different speed, resulting in insufficient provisions for the specified number of patrol days. If the generation of multiple systems depended on a value of a design characteristic, which is either directly taken (i.e. dependent) from a top-level input variable, or indirectly dependent on the upstream generation of another system, then it was concluded that determining the preferred point in the Mathematical Modelling Module (at which that value was set by SUPERB) was important. The selection of the preferred point was intended to minimise the amount of computation required to generate all the relevant SG-level Pareto Fronts. An example of indirect dependency would be the sizing of the air conditioning machinery depending partially on the displacement of the submarine, which would have been selected upstream in the Mathematical Modelling Module of SUPERB.

The sequence in which SG options were selected was seen to be affected by mutual interdependencies. For example, the Propulsion System Group selected depends on the hydrodynamic resistance of the casing, which is affected by the displacement of a submarine (as part of the Strength SG selection).

However, the pressure hull must also wrap around the propulsion system[1] – potentially affecting the selection of the Strength SG. For naval architectural balance to be achievable, the propulsion SG must be able to power the submarine at the required design speeds *and* fit within the pressure hull. In short, the selection of the propulsion SG is affected by the Strength SG and vice versa.

The solution devised to breaking interdependencies was to consider the selection of an SG given the selection of an interdependent SG. It is the overall boat-level performance (using the parts of MoTPC relevant to the particular SGs) that determines the selection of these SG options and not the individual SG's performance. Thus, for any interdependent SG option, the composite performance of all relevant interdependent SG options should be considered – not the sum of two interacting SG options in isolation. As a result, a set of SG-level Pareto Fronts for the (interdependent) SGs was generated, with each SG-level Pareto Front taken to be dependent on the selection of a unique option on the SG-level Pareto Front of the preceding SG. For example, each Propulsion SG-level Pareto Front was derived from each different Strength SG option, linked by differing possible casing and pressure hulls configurations and geometries.

In the example, the Propulsion SG-level Pareto Front could be selected first, and the Strength SG could be the dependent system group or vice versa. For all SGs, given they must be mutually interdependent, some of the top-level input variables used to generate the system groups could affect multiple SGs. The SG, in which such a given top-level input variable should be selected, was seen to be preferred was when it equalised the overall distribution of top-level input variables between the total number of SGs. The designation of given a top-level input variable to different SGs would mean different combinations of top-level input variables amongst the SGs, in order to maintain an equalised distribution. Achieving an equalised distribution of top-level input variables is considered desirable to minimise the amount of computation required to generate all the SG-level Pareto Fronts. This is achieved by minimising the

[1] A nuclear reactor is typically a single size and power, which ensures the pressure hull diameter, has a lower bound. Often a designer has a very limited set of options for nuclear reactor selection (including selecting the number of multiples) and so impacts on the feasible submerged displacement of the boat. However, SUPERB considers a more extensive range of five conceivable but fictional nuclear reactors (and pressure hulls) intended to ensure a wide-ranging concept exploration.

number of SG options needed to be calculated. The mathematics concerning this minimisation of computation for the generation of the SG-level Pareto Fronts (while achieving an equalised distribution) is explained in Appendix D Section D.3. Briefly, its basis is to sum together the total number of SG options used to create each SG-level Pareto Front and the number of SG options to create an NPF. Then using differentiation, determine the 'optimum' number of top-level input variables per SG (assuming an equal distribution).

7.1.3 MEMORY REQUIREMENTS

Generating a large number of SG options could present RAM issues. During the test of the NPF approach it was found that the required storage to accommodate all the SG options could become very large (>30 gigabytes). While the amount of stored data should not be challenging using a modern personal computer, the loading of the data into MATLAB was seen to be problematic[1]. This could be mitigated by using a computer with an enhanced RAM capacity to generate the SG-level Pareto Fronts and by only sequentially loading and unloading specific SG options that had been generated. In five to ten years' time (i.e. 2025), technological improvements are likely to make this specific RAM issue irrelevant.

7.2 RESULTS FROM APPLYING THE NOTIONAL PARETO FRONT APPROACH

The results from applying the NPF approach to produce the refined solution space for the trial run of investigating the SSH(N) concept are shown in Figure 38. It also shows the Notional Pareto Front (red line) and the Balanced Pareto Front (green line) as well as the non-dominated balanced designs from which the Balanced Pareto Front was constructed. Each of these balanced designs (blue circles) was assessed as the best performing design (according to a user-defined metric) for a specific cost point from the pool of potential solutions indicated in Figure 35.

The cost and performance were normalised against a basic submarine, which was the least capable, and cheapest submarine design that could possibly be designed, using SUPERB's mathematical modelling

[1] Typical RAM for a circa 2012 computer is 4 gigabytes

from the pool of unrefined potential solutions in Figure 35. This was done to give the results some context by presenting the results in a readily comparative format. It was considered that it is the comparison of designs, which is of interest at the concept stage of the design process and not the absolute values, which cannot be definitive given the relatively low level of design definition and the limited design assessment possible.

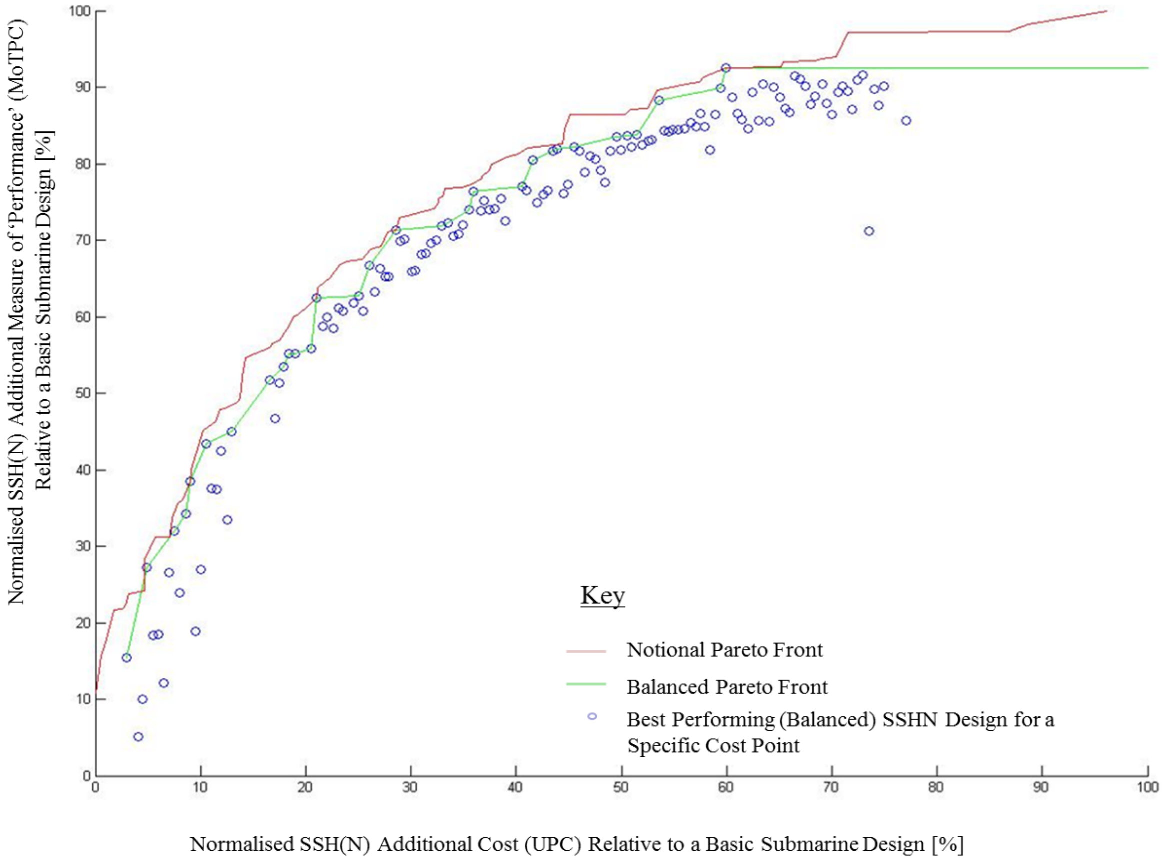

Figure 38 – Comparison of the Notional and Balanced Pareto Fronts from the Test Exploration of the Solution Space for the SSH(N)[1]

The control program was designed to be automatic, once set up. After it has been instructed to perform the determination of the Balanced Pareto Front and all the library data had been pre-calculated (i.e. all the data for the SGs and devising the basis of MoTPC), SUPERB was seen to be capable of generating the results without further designer intervention.

[1] The "Basic Submarine Design" is outlined in Table D2 in Appendix D Section D.3

7.3 SIMULATION TIMES

7.3.1 GENERATING THE ‘SMARTLY’ SELECTED BUT UNREFINED CONCEIVABLE DESIGNS

The time taken to set up control programming in MATLAB to generate the SG-level Pareto Fronts took several days. This was because the Mathematical Modelling Module of SUPERB had to be modified, in order to generate the options for each individual SG and then determine each SG’s Pareto Front. Should the calculation of all the options for an SG here required a greater amount of computation than could be practically undertaken by a single CPU, it was found to be possible to resort to the batching and parallel generation of SG options. However, all the generated SG options had to be subsequently loaded and then collated into a single computer to determine both the SG Pareto Fronts and the NPF for the SSH(N) investigation.

Although the period for the execution of the first stage of the NPF approach took several days, this process only needed to be executed once during the refined solution space stage of SSH(N) design process. Thus, it was concluded that using the NPF to produce the refined solution space in a practical timeframe was a feasible procedure for concept design.

7.3.2 DETERMINING THE BALANCED PARETO FRONT

Subsequent to the generation of a pool of 300,000 unrefined yet conceivable designs from ‘smart’ sampling, the results were calculated over a few days, using a network of 25 modern day CPUs. SUPERB was seen to take typically between 30 and 60 minutes to synthesise and analyse a single design (i.e. execute the entire process of SUPERB outlined in Figure 15 on page 88). A design that sat on the Balanced Pareto Front was typically found for every 50 to 70 synthesised designs. Thus for the test investigation, approximately 7,000 SSH(N) designs were synthesised by SUPERB in order to determine the Balanced Pareto Front. This meant a valid SSH(N) concept design was found approximately once every hour when using a bank of 25 computers.

7.4 'VALIDATION' OF THE NPF APPROACH TEST

7.4.1 'SMART' SAMPLING

The Monte Carlo simulation of the unrefined solution space, first focussed by 'smart' sampling, was seen to model the unrefined solution space, which has already been reduced by using SG-level Pareto Fronts to reject regions unrefined solution space producing infeasible system group options. The shape in the NPF plot on Figure 35 (page 142) shows the pool of unrefined but conceivable options for the design of SSH(N)s and, in particular, the NPF shows a portion of the unrefined solution space to have been eliminated from consideration. This portion was the space above the NPF – i.e. potential solutions which would be high performing and cheap (as estimated using SUPERB's metrics). The rejection of these design was due to the constraints in the Mathematical Modelling Module in SUPERB when creating the SGs that constitute these designs and meet the criteria of high performance and low cost while still being naval architecturally balanced. An example of such an impossible design option would be a very cheap balanced design option costing some UCL £100 million, but having a nuclear reactor producing 100MW shaft power and hence potentially capable of having a very high level of performance (according to the performance metric). This elimination of a portion of the unrefined solution space was considered evidence that the adoption of 'smart' sampling has been vindicated and furthermore made efficient use of computational resources.

The 'bunching' of the unrefined potential solution options in Figure 35 (page 142) towards the NPF and away from the x-axis (cost) was considered further evidence that the 'smart' sampling performed as intended. Designs have been eliminated in the unrefined solution space that could have achieved naval architectural balance following synthesis, but were Pareto-dominated by other balanceable design options. It was concluded that this justifies the use of SG-level Pareto Fronts to establish Pareto-domination. The 'smart' sampling was thus focussed on the region of the unrefined solution space which was of interest, namely, the portion of designs which were likely to be non-Pareto-dominated and naval architecturally balanced.

7.4.2 DETERMINING THE BALANCED PARETO FRONT

The execution of the process outlined in Figure 36 (page 145), using SUPERB to synthesise designs, has been successful in creating a Balanced Pareto Front. By first generating the unrefined Notional Pareto Front, SUPERB has been seen to generate, synthesise and assess designs close to the Balanced Pareto Front – reducing the amount of computation required to find the Balanced Pareto Front. The production of the NPF has successfully produced a set of balanced designs, which are considered either non-Pareto-dominated or approximately close to it. True Pareto-domination of other design options cannot be guaranteed as the NPF approach only samples the unrefined solution space using the Monte Carlo simulation after it has been focussed by 'smart' sampling. This is because sampling means not *every* possible design option is (currently) considered. Those designs on the Balanced Pareto Front could then be analysed for design trends and be taken forward to the next stage of the design process in the Concept Phase.

The non-coincidence of the two Pareto Fronts represents the discarding of design options by the control program, in following the process outlined in Figure 36. These discarded design options were geometrically generated and arranged, and then assessed as infeasible (i.e. unbalanced) by SUPERB. The two lines in Figure 38 appear to be close. However, the small gap between the lines represents many rejected design options since these were very densely packed (illustrated in Figure 35). In the test, the control program typically instructed SUPERB to consider and reject, for a given cost, 50-70 infeasible design options before identifying a valid (i.e. balanced) design option.

The Notional Pareto Front was expected to be close (almost co-incident) to the Balanced Pareto Front in Figure 36 (page 145). While the Notional Pareto Front contained design options that proved unbalanced once synthesised using SUPERB, their component systems were formed of SGs from the SG-level Pareto Fronts using 'smart' sampling. The latter was intended to provide design options from the 'smart' sampling step that were likely to be able to be balanced and non-Pareto-dominated. Thus, it was concluded that the NPF approach had functioned as intended, with the majority of unbalanced or Pareto-dominated designs having been eliminated from consideration using the SG-level Pareto Fronts and the ‘smart’ sampling process as the first step of the NPF approach. The two-step NPF approach is further discussed in Subsection 8.3.5.

7.5 CONCLUSION

Both steps of the test execution of the NPF approach were tested in order to build an understanding of the approach’s theoretical issues and practicalities. Of particular importance was the sequence in which SG-level Pareto Fronts were generated so that unrefined potential solutions could be produced, using a Monte Carlo simulation within the unrefined solution space and focussed by ‘smart’ sampling. The NPF approach was seen to function as intended, with ‘smart’ sampling removing solutions located in regions of the unrefined solution space seen to contain unacceptable. Furthermore, the second step of the NPF approach effectively (i.e. quickly) identified a Balanced Pareto Front from the pool of unrefined yet conceivable design options.

The period required to test the NPF approach was seen to be in the order of several weeks, of which the majority of the time was due to executing the first step of the approach. As the NPF approach is intended only to be executed once during production of the refined solution space, it was concluded that this was an acceptable approach, thus meeting one of the research objectives declared in Subsection 2.7.3.

CHAPTER 8 - DISCUSSION

8.1 INTRODUCTION

This discussion chapter is split into three sections. The first is a high-level discussion examining the work that has been undertaken to meet the research proposal spelt out in Section 2.6. The second section relates to specific points that arose concerning work undertaken to meet specific technical objectives listed in Section 2.7. The final section deals with emergent issues, which have come out of the research undertaken.

8.2 STRATEGIC LEVEL

8.2.1 MEETING THE RESEARCH PROPOSAL

The State of the Art review in Chapter 2 has suggested that problems with no pre-existing designs on which to base solutions, for instance caused by the potential unorthodoxy of SSH(N)s, present the designer with a challenge. Namely, that the two common design approaches traditionally used to generate new submarine designs, as described by van der Nat (1999) (see Subsection 2.4.1) are not considered appropriate. Given the lack of existing SSH(N) designs it seems clear that modifying existing submarine designs to meet the perceived need may not be a suitable approach for such unorthodox designs. It was also concluded that the alternative approach of a small number of focused detail design studies was inappropriate, as the designer would have insufficient guidance with regard to the solution space. This is because incorporating novel technology would introduce significant uncertainty in using best design practice for new vessels and the number of possible solutions is likely to mean a systematic analysis would prove computationally impractical. It was concluded that it was necessary to develop a novel approach (the production of the refined solution space), if relevant knowledge for concept exploration of such concepts as SSH(N)s, was to be captured. This novel approach would sit within the ‘gap’ on a continuum between resources expended and knowledge capture, between the extremes represented by the two traditional approaches (van der Nat, 1999) to the design of a new submarine design.

This novel approach has been captured in the research proposal:

To devise and demonstrate an approach which can produce the refined solution space within a practical timeframe, for the ‘conventional’ concept exploration of novel submarine concepts.

A degree of confidence has been established that the research proposal stated in Section 2.6 appears to have been met by achieving the objectives stated in Section 2.7 to either a satisfactorily complete or partial level. However, further investigatory work is considered necessary to achieve satisfactory completion of all the objectives and hence confirm that the research proposal has been largely met.

The overall structure of the thesis, outlined in Figure 4 on page 28, has been the development of research approaches and tools that have been considered necessary to meet the research proposal stated in Section 2.6. The order of development for these approaches and tools in this thesis has been governed by prerequisites for each layer or stage of modelling and analysis. The OA tool, USGOT, was considered necessary to provide crucial information and knowledge on an unfamiliar technology (UUVs). This, in turn, informed the development of a tool for submarine concept generation (SUPERB) able to consider unorthodox concept designs, such as SSH(N)s. SUPERB needed to be developed to populate solutions for using the proposed NPF approach.

The research has included validation of the individual components necessary for the production of the refined solution space of for potential SSH(N) concept designs which cannot be readily discerned using computational ‘brute force’ interrogation of the unrefined solution space. However, all the components necessary to produce an SSH(N) concept definition have not yet been used together in producing the refined solution space of SSH(N)s, although both the individual components *and* their connections to other components have been tested. The NPF approach has been shown to be able of performing the production of the refined solution space, so is possible to say “a plausible approach” has been devised. The testing of the NPF approach considered a wide range of SSH(N)s, however further investigatory work is required to establish the extent to which these designs studies have distinct and potentially unorthodox styles of designs.

8.2.2 STRATEGIC VIEW OF MEETING THE RESEARCH PROPOSAL OBJECTIVES

The summary of the outcomes of work undertaken to meet the objectives in Table 4 of Section 2.7 is outlined in Table 17.

Table 17 – Table of Research Proposal Objective Outcomes

Objective	Description	Outcome Satisfactory?
	Operational Analysis – USGOT	
1.1	Using operational analysis, obtain new knowledge regarding the nature of the novel payload of UUVs.	**Yes.** Three distinct scenarios have been simulated to provide guidance on the size of UUV payloads. These would appear to be 50-100 tonnes in size and highlighted the importance of larger UUVs
	A 'Generic' Submarine Design Tool – SUPERB	
2.1	SUPERB can be used to produce submarine concept solutions in the unrefined solution space	**Yes.** SUPERB's Mathematical Modelling Module has generated unrefined potential designs.
2.2	SUPERB should be capable of generating the wide variety of concepts in the unrefined solution space for a novel vessel, such as an SSH(N). The tool needs to be shown to be 'flexible'.	**Mostly.** SUPERB generated putative balanced SSH(N)s, a version of BMT's SSGT concept and versions of Bradbeer's SSK(N) concept. SUPERB was able to be quickly modified and additional knowledge added to produce these novel design concepts, thereby demonstrating flexibility. The simplifications made to the PH geometry in SUPERB is considered to currently restrict the variety of unorthodox designs SUPERB can explore.
2.3	Need to devise an internal submarine arrangement approach that is highly automated (i.e. computer-based) and able to produce conceivable arrangements.	**Yes.** The Compartment X-Listing approach is computer-based and has been shown to produce conceivable arrangements.

Objective	Description	Outcome Satisfactory?
2.4	SUPERB needs to be able to be interrogated (i.e. not be a ‘black box’) so it can be examined and verification provided that the processes and assumptions in the tool’s construction are valid for the designs it generates.	**Partially.** The programming in MATLAB for SUPERB should allow the user to monitor the actions of the computer code for an individual design. However, this needs to be tested for confirmation. It is considered that there are practical limitations to the level of interrogation should SUPERB produce thousands of designs.
	Producing the Refined Solution Space (NPF Approach)	
3.1	The NPF approach can address a range of concept designs with potentially differing styles.	**Partially.** The test results of the NPF approach considered a wide range of SSH(N) designs. However, further investigation needs to be undertaken to determine if these designs had sufficiently (i.e. significantly) distinct and differing styles.
3.2	Need to devise metrics (‘performance’ and cost) that are appropriate in determining ‘preferred’ concept designs.	**Yes.** The MoTPC and UCL’s costing scheme have been shown to meet this objective.
3.3	The NPF approach can produce the refined solution space and facilitate ‘conventional’ concept exploration of novel concepts, such as SSH(N)s.	**Partially.** The test results of adopting the NPF approach have shown a set of non-Pareto-dominated concepts could be found using it. These results defined a refined solution space. A full test ‘in anger’ of a novel submarine concept, which undergoes a reasonable concept exploration process, would verify the NPF approach for novel submarine concept work.
3.4	The NPF approach can be performed in a practical timeframe of a few weeks.	**Yes**. The trial execution and setting up of SG-level Pareto Fronts took approximately three weeks to set up and be calculate.

The objectives called for a tool (SUPERB) that could generate essentially generic submarine concepts and determine their naval architectural balance to the level appropriate at the concept definition. Such a tool was considered to be necessary to be used by the NPF approach for populating the unrefined solution space for SSH(N)s. Chapters 4 and 5 presented and partially validated SUPERB, using the SSH(N) concept as an example.

The approaches and tools have all been developed 'from scratch' using the programming language MATLAB, making their interrogation relatively easy, as the code is readily accessible. This is seen to meet one of the objectives outlined in Table 4 in Section 2.7. All sections of the SUPERB computer code[1] are unrestricted, allowing the code's actions to be monitored and modified at any stage of either development or execution. However, if hundreds of designs were to be generated to feed the NPF approach, then there would be practical limitations to comprehensively monitoring the actions of SUPERB's code. However, key assumptions and equations have been documented in Appendix F.

Within the limitations of the equipment and physical features that SUPERB has been programmed to mathematically model, SUPERB has been shown to be capable of generating a variety of designs – including, crucially, some with unorthodox styles of designs. This exploration has been reasonably wide ranging to avoid the unrefined solution space being 'artificially' constrained by just orthodox solutions, which would have meant the concept exploration might be limited to specific regions of the solution space and, in so doing, miss the advantages that more unorthodox designs could reveal. The results shown in Chapter 5 suggest that the Compartment X-Listing feature is capable of considering both orthodox and unorthodox submarine arrangements. This strengthens the argument for SUPERB being of a (mostly) generic nature. The work in Chapter 5 also indicated that the first Arrangement Step (Style Preferences) could produce unorthodox arrangements (see Section 5.3) and so appropriate to producing unorthodox submarine concept designs. The work described in Chapter 5 additionally showed that the application of Functional Constraints in the second Arrangement Step, given an appropriate selection

[1] SUPERB is held at the DRC, Department of Mechanical Engineering, UCL.

of Functional Constraints within the Constraint Profile, should not force an unorthodox arrangement to become a more conventional one. Thus, overall it was concluded that the Compartment X-Listing approach is capable of considering both orthodox and unorthodox submarine arrangements. Thus, the NPF approach is considered capable of considering unorthodox designs, as it employs the SUPERB tool to undertake population of the unrefined solution space. This meets the objective in Table 4 of Section 2.7 which calls for the approach mentioned in the research proposal in Section 2.6, namely to "consider a range of concept designs with potentially different styles".

In carrying out concept exploration of complex vessels with sufficient confidence that the refined solution space has been correctly identified, in that it has been shown to contain a set of concept design solutions that appear to explore that space, then the unrefined solution space would feasibly have been seen to be extensively explored. The size of the unrefined solution space in which potential designs initially reside implies an infinite number of unrefined potential solutions relevant to the concept exploration. As discussed in reviewing the State of the Art, and shown mathematically in Subsection 6.3.2, generating models of a very large number of potential designs was computationally infeasible. However, it was considered possible to explore the unrefined solution space extensively at a sufficient level of discrimination.

This exploration has been tackled in a number of ways in order to meet the research proposal. Firstly, SUPERB has been devised to provide a novel arrangement method, called Compartment X-Listing (meeting an objective in Subsection 2.7.1), which is automated to minimise the time-consuming direct instruction from a designer. This novel arrangement method was intended to produce a 'good enough' arrangement, as opposed to searching for an 'optimised' one. Such arrangements ought to be naval architecturally balanced and able to satisfy other issues, such as efficient movement of personnel and equipment within the submarine. However, arrangements produced by Compartment X-Listing cannot be considered 'optimal' (in the engineering sense of meeting an objective). Given that in the Concept Phase of the design process, it is considered impossible to construct reliably an accurate arrangement metric, due to the low level of detailed definition, the multi-rolled nature of naval vessels and the divergent stage of the process. The testing of the NPF approach, presented in Chapter 7, is considered to show the populating of the refined solution space is likely to be computationally demanding. The time taken to explore a novel concept, such as an SSH(N), was shown to require executing SUPERB many thousands of times within the NPF approach.

In order to handle the impossible number of potential designs in the unrefined solution space, a ‘smart’ sampling stage was introduced into the NPF approach (see Subsection 6.4.2). The application of some constraints at a system group level using pre-existing knowledge, such as the immutable laws of physics, could lead to the rejection of regions of unrefined solution space, which correspond to apparently infeasible designs. Using the Pareto Front representation at the system group level enabled further exploration of potential SSH(N)s. This then eliminates regions of unrefined solution space containing Pareto-dominated system group options and, by extension, whole submarine designs. As a result, these submarine designs are no longer in consideration. The NPF approach, and especially the ‘smart’ sampling, is intended to make an efficient use of the readily available knowledge. This strongly suggests as much accessible knowledge as possible is compiled before embarking on the exploration of a novel design concept. Following the focusing of the unrefined solution space using ‘smart’ sampling, the design solutions in the remaining solution space can be modelled, using statistical sampling, to generate a pool of design options from which the NPF can be identified. Subsequent analysis of the whole boat level Balanced Pareto Front could then be used to produce a set of balanced concept designs on which to base ‘conventional’ concept exploration. However, performing this analysis was considered to be is outside the scope of this research.

The current search approach used to find the BPF employs a relatively crude method. It has been used to demonstrate viability in this research; however, any actual research investigation could use a more powerful search algorithm to increase the speed without having to resort to greater computational power. This would be a significant improvement in the approach. For example, considering holistically the generation of unrefined design solutions (i.e. both stages of generating the NPF) across the solution space might be far more computationally effective[1]. Many possible search algorithms exist for such a task, not just genetic algorithms (see Sen & Yang (1998)).

8.3 TACTICAL LEVEL

8.3.1 INTRODUCTION

Having considered the research from a strategic point of view in the preceding section, the research at a tactical level is now considered. This discussion of the issues mirrors the sequence in which different topics have been discussed. As discussion points have been covered in the preceding chapters, a summary is provided here. A more extensive discussion of the tactical issues can be found in Appendix I.

8.3.2 ISSUES RAISED BY THE STATE OF THE ART REVIEW

8.3.2.i Need for a 'Generic' Submarine Design Tool

- SUPERB has been labelled a "generic" tool, as it is considered it should be able to generate novel submarine concept designs within the limits of practicality and the available information,
- It was proposed that SUPERB should produce designs (including arrangements) in a highly automated manner. SUPERB, however, is still directed by the designer, as the designer provides *a priori* knowledge. This implies design decisions are split between those made by the designer and those hard-wired into SUPERB.
- SUPERB has been designed to be readily interrogated (i.e. it is not a 'black box') since the computer code has been entirely and accessibly written in MATLAB, and is intended to ensure that the flow of data during the execution of SUPERB can be easily monitored. However, this currently needs to be tested for confirmation.
- Knowledge can be readily implemented due to the generic nature of encoding the properties of the design's compartments. This should make incorporating new properties into the arrangement method (Compartment X-Listing) virtually seamless.

[1] This is explored in more detail in the next section of this chapter.

8.3.2.ii Arrangement Approach

- A procedure for generic submarine design based on Burcher and Rydill's (1994) procedure was adopted for the concept design of novel submarines. The procedure, however, does not cover how to arrange compartments and equipment it, merely generates them. Thus, producing an arrangement approach was considered in its own right (Compartment X-Listing).
- It was concluded that the Compartment X-Listing approach should control the order in which compartments are arranged, under the influence of the Constraint Profile from the first and second Arrangement Steps.
- It was concluded that a bespoke arrangement approach, based on using DBBs, ought to be devised to perform heavily automatic arrangements. It was considered that an 'automatic' arrangement would still require some limited (but not direct) human direction upstream in the design process, such as for defining tankage objects.
- Genetic algorithms using whole-boat level objective functions were concluded to be inappropriate. The approach was also deemed impractical for producing arrangements for consideration of a broad range of potential designs. It is considered that this suggests that an arrangement approach does not need further 'optimisation' using a genetic algorithm.
- TU Delft's Packing Approach (van Oers, 2011) uses a genetic algorithm to produce layouts that rely on some MOE at the local arrangement level, using a database of relative locations. This is similar to the second Arrangement Step in the candidate's Compartment X-Listing approach. However, the advent of Style Preferences to promote arrangements that a designer might consider favourable at the whole-boat level is considered unique.

8.3.2.iii The Nature of Approaches to 'Conventional' Concept Exploration for Submarines

- It was concluded from Chapter 2 that 'conventional' concept exploration using an approach with discrete designs possessing arrangement is advantageous over SBD if the designer has not been constrained beforehand on the definition of the refined solution space

- Furthermore, it is considered that without a DBB level of concept definition, it is unlikely that the designer can obtain a worthwhile understanding of the impact of new technology on whole ship (or submarine) design in the Concept Phase of design.
- The NPF approach's second stage, during which the Balanced Pareto Front is determined, has been seen in the test exploration of the SSH(N) concept in Section 7.2 to produce a focused set of non-Pareto dominated and concept level balanced designs to which a discrete architecturally led approach could be applied to inform concept exploration.
- The successful incorporation of knowledge obtained from the USGOT simulations in the test exploration also suggests that such an approach could address concept exploration, including unorthodox submarine designs.

8.3.3 ISSUES RAISED BY USGOT

- Simulations undertaken indicate that UUV payloads would have a large total displacement (typically in excess of 50 tonnes), and would be a radically different from the current UUV payloads being considered for submarines.
- The USGOT tool was limited to considering a few example UUV missions, considered to be heavily resource taxing and demanding highly capable UUVs. It is conceivable that during an actual investigation into the SSH(N) concept, a less restricted range of UUV missions might be adopted.
- Pre-calculating the effectiveness of a limited number of UUV payloads (i.e. before using SUPERB to generate a SSH(N) design), was seen to preclude undertaking very large and computationally demanding batch runs in SUPERB of every possible combination of numbers of different UUV for every design generated.
- The importance of Category A UUVs points to where a large portion of the design effort should be focussed in order to incorporate these UUVs and their supporting equipment into the overall SSH(N) design.

- To date, very few UUVs above around 3,000 kg displacement have become available (see Appendix B Section B.1). It is anticipated that as unmanned underwater operations become more commonplace, further developments of large UUV/MUVs will occur to facilitate more complex multi-UUV operations, such as those simulated by USGOT.

8.3.4 ISSUES RAISED BY SUPERB

8.3.4.i Mathematical Modelling Used

- The utility of the Mathematical Modelling Module in SUPERB has been limited by the range of equipment and physical features that has been programmed into it to date. SUPERB could be extended to model different pressure hull configurations and ranges of unorthodox designs in order to explore a wider region of unrefined solution space.
- The Mathematical Modelling Module of SUPERB was successfully altered to approximately recreate the triangular casing used on the BMT SSGT (2015), demonstrating the ability ('flexibility') of SUPERB to be programmed to consider unusual physical features. It is considered that this could be important if SUPERB is to be used as a research tool.
- Currently, the Mathematical Modelling Module is limited by the data and knowledge from which the mathematical models are constructed. Thus, SUPERB cannot access unrefined solution space regions for which data is lacking.

8.3.4.ii Arrangement Approach

- Currently, it can only be concluded that Compartment X-Listing is a plausible submarine arrangement approach, which may be faster and more designer responsive than any currently accessible alternative.
- The Constraint Profile will strongly influence the arrangement produced using Compartment X-Listing. The significant differences seen in the 100 generated SST arrangements by Compartment X-Listing (see Figure 28 on page 126) indicated that the choice of compartment locations relationships made by the designer is important.
- A model of the 'true' distances between compartments for the 'logistical effort' could be constructed. It is considered that adding complication to the 'optimisation' of the disposition of

compartments might increase the calculation time to what may well be considered unsatisfactorily (e.g. about ten minutes).

- If heterogeneous decks have to be modelled by SUPERB, then generating a layout is likely to become more complicated.
- The overall agreement between the original SSKN produced by Bradbeer (2015) and a SUPERB-generated arrangement indicated that a relaxed Constraint Profile potentially facilitates the generation of unorthodox arrangements.
- The good agreement in replicating Bradbeer's SSKN concept suggests that SUPERB can reproduce to some degree the actions of the designer in producing a submarine internal arrangement. This is considered fundamental if a large number of novel concept designs, are to be generated by SUPERB.
- The packing stage currently makes simplifications to simplify the creation of the X-List in the preceding two Arrangement Steps. These were considered appropriate for broad level of detail definition at the concept level of design, but not suitable for subsequent stages in the design process
- The approach for packing used by SUPERB cannot be said to be truly generic, as it has not been verified against a reasonable number of pressure hull geometries that could be said to represent *all* likely geometries.
- SUPERB cannot currently represent complex geometry, such as the forward MBT wrapped around the dome bulkhead and pressure hull transitions.

8.3.4.iii Analysis Module of SUPERB

- The problem arising from the limited analysis appropriate during the concept exploration stage of the design process has been explored by Andrews (2013). Andrews pointed out the limitations and risks of analysis should be appreciated by the designer because there are likely unknown constraints on the design.
- Currently, SUPERB lacks the ability to assess the influence on a concept design caused by hydrodynamics, and, in particular, manoeuvrability related aspects. This introduces a degree of

uncertainty into the analysis of a design, which could in turn, significantly affect requirement elucidation, and ought to be investigated further.

- Survivability from flooding is another design aspect that is not considered using SUPERB's analysis module, as it requires substantial modelling (Burcher & Rydill, 1994). However, with the generation of an arrangement by Compartment X-Listing, it could be possible to perform an assessment.
- If SUPERB is used 'in anger' for the exploration of a submarine concept, a specific cost model would be implemented, instead of the one used in this research.

8.3.5 ISSUES RAISED BY THE NOTIONAL PARETO FRONT APPROACH

8.3.5.i Restriction on the Accessible Unrefined Solution Space

- The effectiveness of the proposed NPF approach in exploring the unrefined solution space for a novel design is limited by the mathematical modelling of the systems (and subsystems) that make up a given design being investigated.
- Furthermore, SSH(N)s more readily bound the solution space compared to ships, as the design of submarines and UUVs are heavily constrained by the physical environment in which the operate.
- As computer speeds increase, the amount of computation possible in a given time should increase. This, in turn, should allow a greater range of sampled values within a given timeframe.

8.3.5.ii Statistical Sampling of the Unrefined Solution Space

- Slovin's formula (Altares, et al., 2003) for determining the statistical confidence level of a sampled population has been used to identify the sample size for generating the pool of potential designs through 'smart' sampling.
- The normal distribution was adopted as this is typically used in applications where a population is sampled to identify trends that are not readily apparent, such as for political polling. The application of the normal distribution in political science has been described by King[1] (1988).

[1] King (1988) said "*for continuous variables in ordinary regression analysis, the normal distribution is often … justified as the sum of many unmeasured variables*"

8.3.5.iii ‘Smart’ Sampling Eliminating Pareto-Dominated and Infeasible Design Options

- While ‘smart’ sampling has been assumed in Subsection 6.3.3 as statistically adequate to cover and represent the region(s) of interest, it still allows the possibility of computationally expensive synthesis of unbalanced submarine designs.
- The shape in the NPF plot of Figure 35 indicated a portion of the unrefined solution space with potential designs pre-eliminated from consideration due to violating SG constraints in the Mathematical Modelling Module of SUPERB.
- The ‘bunching’ of the unrefined potential solution options in Figure 35 towards the NPF could be taken as evidence that the ‘smart’ sampling feature performs as intended.
- The high density of design options (evidenced by the near coincidence of the NPF and Balance Pareto Front) suggests that a proportion of the pool of unrefined potential solution options in Figure 35 is not close to the Balanced Pareto Front, indicating that their generation is ‘wasted’.

8.3.5.iv Reasons for Confidence in the Adopted Measures of ‘Performance’ and Cost

- The reason for not using a specific cost and a set of whole-boat ‘performance’ features as input is that in doing so implies the designer knows *a priori* where the solution designs may approximately be found. This would be contrary to the raison d'être of the NPF approach.
- Submerged displacement was seen not to exclusively drive cost and ‘performance’.
- It is recognised that the MoTPC is based only on one set of weightings, which may be subject to bias. A sensitivity study could be undertaken to establish the effect of bias on the overall conclusions if the NPF approach was used for an actual investigation.
- By just considering one design, all future work on developing subsequent SSH(N) designs might be driven by the peculiarities of that design. Some of these peculiarities may point to a design solution that might be near the ‘edge of the cliff’ in terms of the cost versus performance. Furthermore, when avoiding the ‘edge of cliff’, consideration ought to also be paid to scope for altered requirements, which could force a previously ‘safe’ design solution to the cliff edge.

8.3.5.v Generating System Group Level Pareto Fronts for Producing Potential Designs from 'Smart' Sampling

- It took an estimated three to four weeks for 'real' SG-level Pareto Fronts to be generated. It was concluded from this that it is suitable to use 'real' SG-level Pareto fronts when using the NPF approach to undertake the exploration of a submarine concept,
- The sequence in which SG options were selected was seen to be affected by interdependencies. Thus, for any interdependent SG option, the composite performance of relevant interdependent SG options should be considered – not the sum of two interacting SG options in isolation.
- For SGs, given they must be interdependent, some of the top-level input variables used to could affect multiple SGs. The SG in which a given top-level input variable should be specified was seen to be preferable when it helped equalise the overall distribution of top-level input variables, since limits computation.

8.3.5.vi The Robustness of the NPF Approach

- The two fronts in Figure 38 appear to be close. However, the small gap between the lines represents many rejected design options, as the options are very densely packed.
- It was concluded that the NPF approach had functioned as intended, with the majority of unbalanced or Pareto-dominated designs having been eliminated from consideration using the SG-level Pareto Fronts in 'smart' sampling.
- SSH(N) designs of potential interest could be recreated in Paramarine to obtain a greater degree of confidence in their balance. This would confirm that SUPERB has reasonably represented SSH(N)s to a concept level of definition and therefore, the BPF does contain balanced designs from which to conduct 'conventional' concept exploration.
- The solutions on the BPF ought to be close to being 'truly' non-dominated designs (as would be shown by a near 'perfect' metric for defining their costs and performances).

8.4 EMERGENT ISSUES

8.4.1 INTRODUCTION

The final section of this chapter largely covers issues that have emerged out of the research but do not correspond to a specific part of it. This section first covers the usability of the computer approaches and tools from this research. It ends with a discussion on the wider insights gained into devising complex computer-based approaches and tools considered necessary for undertaking investigatory research into the novel SSH(N) concept.

8.4.2 USABILITY

The approaches and tools developed in this thesis have all been programmed in the coding language MATLAB. MATLAB is a commercial product that is currently commonly used by a number of organisations and widely available for Mac OS, Linux and Microsoft Windows operating systems. As a result, the code used to develop these approaches and tools could easily be run on a number of machines. This would be particularly useful for running concurrent batches of design synthetisations during the execution of the NPF approach, as described in Subsection 7.3.1. The vast majority of the code written for these research tools could be written in other programming languages. However, MATLAB was chosen due to its wide array of built-in functions that might need to be programmed 'by hand' if other languages were adopted. For instance, a function to identify polygons within polygons used to ensure that an arrangement is compact during the execution of the packing stage of the Compartment X-Listing approach would likely be difficult to replicate 'by hand'. MATLAB's efficiency in solving equations involving matrices, which can change in size depending on the peculiarities of each arrangement produced by using Compartment X-Listing, was seen to be particularly useful when creating SUPERB.

The numbers of CPUs on which the NPF approach can be executed within a given period have an influence on the extent to which the unrefined solution space can be explored. The greater the computational power, the greater the number of unrefined potential solutions that can be synthesised by SUPERB (as this is computationally relatively expensive) and thus, the greater the range of sampled continuous top-level input variables with discretised values. This is turn, reduces the amount of unrefined solution space that is inaccessible by such sampling.

The computer code for SUPERB and the NPF approach are controlled by the designer selecting inputs and then choosing to execute the computer programs. No front-facing interface program, such as a graphical user interface (GUI), has been constructed to facilitate the direction of the execution of the computer programs. A GUI for USGOT has been coded and already used by teams in UCL's postgraduate submarine design course. Constructing a GUI for the simple input of top-level input variable values to execute SUPERB is expected to be a relatively simple task, as MATLAB provides a tool to construct a GUI from which to run its code.

It is conceivable that a MATLAB program could be constructed to collate the input and output of top-level input variables used for the construction of each SG-level Pareto Front. This program could then analyse and mathematically optimise the flow of these variables between system groups (as has been described in Subsection 7.1.2) to minimise the computational demand. The consideration of additional top-level input variables for a system group would significantly increase the possible combinations of system group options**.** For interdependent system groups, the analysis of the flow of variables during the generation of a set of SG-level Pareto Fronts should provide insight into the order in which system group should be addressed. Achieving an equalised distribution of top-level input variables amongst the system groups is desirable in minimising the computation required to generate all the SG-level and Notional Pareto Fronts, so this could be the goal of any efficient software production.

Modifying the code for the computer-based approaches and tools that have been presented would not be trivial. For example, the modification of SUPERB to generate an interpretation of BMT's SSGT design (BMT Defence Services, 2015) took a few days to incorporate and verify. This is because many of features of the tools have been hard-coded[1] into the program's structure. Thus, an in-depth knowledge of the structure of the program is required to undertake any modification. An example of this is the

[1] Hard-coded is analogous to "hand-wired". Hard-coded has been defined by Dictionary.Com (2010) as "*a data value or behaviour written directly into a program, possibly in multiple places, where it cannot be easily modified*".

mathematical representation of pressure hull configuration in SUPERB. Currently, SUPERB can only consider single or twin (e.g. equal hulls arranged side by side) pressure hulls. If a triple pressure hull configuration was to be designed using SUPERB, all the subprograms of SUPERB relating to arrangement would require extra code to describe this new geometry. The Mathematical Modelling Module of SUPERB would also require modification so that the modelled characteristics of relevant equipment and physical features then could reflect a triple pressure hull arrangement.

It was suggested in Section 7.3 that the execution of the NPF approach would take around three weeks to explore the unrefined solution space for a typical SSH(N) investigation. The time for execution will vary depending on the available computational resources, the peculiarities of the novel concepts and, in particular, the available knowledge about the new concept and its novel aspects. With the example of the creation and subsequent simulations using it, some preliminary work may be necessary before populating a new unrefined solution space with potential designs. However, since the production of the refined solution space using the NPF approach is intended to be undertaken only once for a given investigation, due to the long execution time for the NPF approach, this is considered acceptable.

8.4.3 MISCELLANEOUS ISSUES

It is recognised that there has almost certainly been design work performed on both SSH(N)s and UUVs that is classified or commercially sensitive. This work was thus inaccessible for use within this research. Of particular relevance is a lack of data able to be consulted during the creation of the Mathematical Modelling Module of SUPERB. The higher the quality of data used by the mathematical models, the more reliable the data such as the description of the equipment and physical features that comprise a design. Similarly, the more accurate the knowledge of systems and equipment, the more realistic the mathematical modelling which describes them. This is a case of the maxim “garbage in garbage out” (GIGO) (Butler, et al., 2010).

Any future modifications to the SUPERB program are likely to be difficult, as this requires knowledge of the program’s structure (i.e. its ‘inner workings’). This modification is currently made more difficult by the long time required to execute SUPERB, or more accurately, running certain subprograms such as the first Arrangement Step in Compartment X-Listing (see Figure 18). This can hinder the implementation of modifications as the feedback time becomes extended. As mentioned in Subsection 6.3.3, a continuation of Moore's law (1975) might provide increasing computational power in the future at such a rate that the feedback times from executing SUPERB reduce, and thus reducing the debugging time. As debugging is currently a particularly troublesome process, there is the potential to inhibit certain modifications being implemented (and thus limiting the utility of the tool). It was noticed that modifications of SUPERB that required code to be developed 'on the fly' (as opposed to being developed separately), took significantly longer to implement. The duration was typically of the order of a few hours compared to a few minutes for the separately developed code. The code developed separately enjoys a 'closed' environment, reducing both the runtime for verification and less code for inspection – making it easier to locate errors.

The publications to come out of the current research have been listed in Appendix J.

8.4.4 WIDER INSIGHTS

8.4.4.i Combined Human and Computer-Based Design

The influence of the designer, using a computer-based design tool such as SUPERB, is considered critical with respect to two related processes in the design procedure. Firstly the direction of arrangement of compartments to produce a 'good' layout (i.e. one that is likely to be naval architecturally balanced and favourable with regard to human factors), and secondly, the sequence of steps taken to achieve balance from an unbalanced design. A designer with the knowledge from previous other designs has a repository of knowledge with which they are familiar from applying this knowledge to different designs, some of which might have been novel concept designs.

A major disadvantage of the human designer is considered to be that they are slower in executing a fixed procedure than a modern day computer. For example, for submarine design, a computer would be faster at executing procedure similar to that proposed by Burcher & Rydill (1994). From the State of the Art review (Chapter 2), it was considered that the exploration of the unrefined solution space for a novel concept would require a very large number of designs to be considered and a designer could not undertake such an exploration without computerised assistance. Thus, an underlying task in the development of the approaches and tools in this research has been the split between the designer and computer-based execution. The goal was to achieve a synthesis that provides both a sufficient speed of program execution while leveraging a designer's two strengths: the ability to inspect a design directly and thus verify output, and a designer's creativity to generate designs preferred by the designer. It was considered that these strengths are most acute in the generation of arrangements. Thus, the computer might place torpedo tubes in the centre of the arrangement and away from the pressure hull, unless this has been programmed or a constraint inserted as an input. A designer will already know not to do so from experience.

By using the designer's input into Paramarine to generate concept designs (including arrangements), it would be insufficiently fast to conduct the wide-ranging exploration of the unrefined solution space for a novel concept. However, it was considered that a designer undertaking the generation of a wide range of concept designs would still 'mechanically' perform a number of actions that could be replicated by a computer. Thus, the computer can be 'taught' (i.e. programmed) to place torpedo tubes so that they penetrate the pressure hull. As discussed in Subsection 4.2.2, SUPERB already has been shown to be able to take automatically some basic steps to balance subsequently an unbalanced synthesised submarine design[1] by encoding the specific reasons for a design being unbalanced to determine a sequence of steps needed to be taken to achieve naval architectural balance (if it is possible).

The designer can then be spared this work, and instead, their 'expensive' time can be reserved for other tasks, such as inspecting the design output and directing any alterations they deem necessary. The change from a human fully generating a design to combined computer and human generation can be observed already. For instance, Burcher & Rydill (1994) have observed that for submarine design, computer graphics have already superseded drawing by hand.

8.4.4.ii Approaches to Exploring Physically Large and Complex Systems

It is considered that the approaches outlined in this research also apply potentially to any physically large and complex (PL&C) system, of which a submarine is one example. A PL&C system consumes

[1] Schematics of the subroutines executed by SUPERB to balance a design are presented in Appendix D Section D.7.

significant resources to produce, which combined with its physical scale, usually results in bespoke designs. This in turn, strongly discourages solution development through the creation of prototypes as they are not cost effective, as remarked on by Andrews (2012). Furthermore, Andrews noted the physical size of the system leads to on-site facilities for manufacture, which themselves can be complex and expensive. This is in contrast to non-physical systems (e.g. software) where alterations to the system are virtually free and the manufacturing tools (i.e. computer programming languages) typically already exist and possess the flexibility needed to be suitable for the creation of different PL&C systems - also, unlike smaller manufactured goods (equipment) and vehicles (cars, planes etc.) which have several full-scale prototypes tested before manufacture begins in factories.

The nature of investigating an SSH(N) is an example of a high complexity, (potentially) high novelty and highly latent feedback problem. Feedback latency is the time taken for information concerning development to get to the designer. The potential for novelty amounts to the same implication as actual novelty, needing a wide search of the solution space. As the SSH(N) has these three properties, the proposed approaches and tools in this research have been developed to meet these needs.

A low level of novelty would suggest a solution based on evolving an existing design, and so it becomes appropriate just to incorporate any required modifications. For example, the evolutionary approach was suggested by van de Nat (1999) (see discussion in 2.4.1) as one traditional method of producing designs for new submarines. As explained in the State of the Art review, the potentially high degree of novelty that might be attached to an SSH(N) precludes the evolutionary approach to design.

If a given design problem has a lower level of complexity, such as for an evolutionary ‘type’ ship, it is considered that the selection of an approach would reflect the less complex nature of the problem. Even if the problem has a high latency feedback and/or a high level of novelty, the less complex nature of the problem should allow the designer to converge quickly on a solution, as a ‘good’ starting point is known. This is turn would require little feedback, eliminating any issues with latency. An example of this would be the adoption of UCL’s DBB approach and use Paramarine to generate a handful of designs and converge on a solution.

If the problem possesses a high level of complexity <u>and</u> a high degree of novelty, generating a handful of Paramarine designs is likely to be insufficient to explore the solution space satisfactorily. The high level of novelty precludes the evolutionary approach to submarine design. As a result, an alternative approach to exploring PL&C systems (with high degrees of novelty), such as SSH(N)s, has to be considered. This is the 'continuum' outlined by van de Nat (1999), which currently suggests two options to developing a suitable approach.

A problem with high complexity and high novelty cannot be solved with computational 'brute-force', although a sub-problem with fixed parameters, such the OA tool: USGOT, could be separated from the overall problem to partially reduce the complexity. It would also reduce the risk in a novel concept, by providing some information into the novel aspect of a design problem. This would involve generating solutions very quickly and analysing a large dataset. For instance, UUV payloads are deemed to be attractive. Such an approach would have a low latency (i.e. quick feedback) during development as it could afford to be relatively 'dumb'. Thus, high computational power could overcome any lack of subtlety in the approach. The reasons why this would not be appropriate overall for novel PL&C systems, such as the SSH(N), have been outlined in Subsection 6.3.3. In short, the complexity means generating each design takes too long, and the novelty means that a large number of different designs are required to explore satisfactorily the solution space, plus the need de-risk the incorporation of novelty. So a novel and complex problem will thus almost inevitably have a high latency of feedback as well.

The NPF approach developed in this research could be considered for research into any PL&C system with a (potentially) high degree of novelty. The focusing of the solution space by using 'smart' sampling can be considered a virtual shortening of the feedback time, as inappropriate solutions are rejected quickly without the slow process of synthesis by SUPERB (see Subsection 7.3.1). The potential novelty is indicated by the inclusion of a significant UUV payload into the submarine design, as suggested by the simulations from the USGOT OA tool and the range of values that the 30 top-level input variables adopted for the limited testing in Chapter 7. The SUPERB tool, and, in particular, the Compartment X-

Listing approach, are intended to provide the necessary detail (and thus complexity) for early-stage concepts to be adequately evaluated during concept exploration.

Nonetheless, the high levels of complexity, novelty and latency made the development of these tools a challenging process. For instance, the development of USGOT to provide information on the novel aspect of SSH(N)s was seen to be necessary, as no appropriate tool was accessible. Of particular complexity in SUPERB was the modelling of the interplay between different major sub-systems for a PL&C system. The latency of generating a design ensures that developing a novel approach from 'scratch' would be a slow process. The high degrees of novelty and complexity mean the development of an appropriate approach would not be straightforward, as the solution would not be readily obvious. The approach could be 'evolved', with incremental steps causing other parts of the approach to become redundant or require further development An example in SUPERB's development is the modification of the packing algorithm to address the packing compartments in the two pressure hulls of a twin pressure hull submarine.

The corollary is that the development of a suitable approach to exploring novel PL&C systems at the concept stage is a resource-intensive process – but not necessarily an impossible one. Therefore, the research approach and tools developed for this research might provide a basis for a possible 'blueprint' for the undertaking the exploration of other novel PL&C system concepts in the future.

CHAPTER 9 - CONCLUSION AND FURTHER DEVELOPMENT WORK

9.1 CONCLUSIONS OF THE RESEARCH

The challenge of incorporating a novel technology (UUVs) into submarines suggested traditional approaches to concept exploration are inappropriate, as the incorporation of novel technology requires unorthodox styles of design to be considered. Simulations to gain an understanding into UUVs using a bespoke UUV OA tool (USGOT) have indicated that an SSH(N) could feature a large UUV payload totalling approximately 100 tonnes. Thus, it was concluded that such SSH(N)s are likely to be correspondingly large, at greater than 5,000 tonnes submerged displacement. The innovative research approaches and tools proposed are intended to produce the refined solution space revealing design trends and enabling concept exploration of novel concepts with greater confidence. A novel approach of modifying a nominal Pareto Front representation for complex concept designs called the Notional Pareto Front (NPF) approach, used with a ‘generic’ submarine design tool (SUPERB) to generate synthesised designs, is proposed as an innovation in marine design practice.

The NPF approach seeks to produce the refined solution space by making an efficient use of the readily available knowledge. The exploration of the SSH(N) concept appears to show that the research proposal (Section 2.6) has been essentially achieved. The test of the NPF approach has indicated that such a concept exploration study should be possible in a few weeks – making the approach practical to inform concept exploration. Although a comprehensive test of the NPF approach has not been presented, the individual elements (USGOT, SUPERB and NPF approach) have each been subjected to validation. Thus, there is a reasonable degree of confidence that the research proposal has been met by the presented approaches and tools.

The ‘generic’ submarine design tool (SUPERB) has been shown to be capable of addressing a range submarine design styles to facilitate a broad exploration of the unrefined solution space. The construction of SUPERB and in particular, the novel and largely automatic Compartment X-Listing arrangement approach incorporated within it, has been partially validated. This has demonstrated that the latter is capable of producing ‘good’ but not formally optimised arrangements – some of which could be described as unorthodox. It has been recognised with this research that SUPERB’s output is currently limited by the analysis undertaken being generally appropriate to a concept level of design definition. This limits results with regard to a full investigation of the main relevant aspects of performance and function. Nonetheless, the work presented has indicated that it is possible to construct a highly automated tool for concept generation of novel submarine designs and by the NPF approach can inform marine design research. It is therefore considered that the key objective that the submarine research tool SUPERB has been produced with a sufficiently computer-based capability has been met, and this enables a designer to take advantage of future faster computation capabilities likely to be provided by ongoing developments in computer technology.

9.2 PROPOSED IMPROVEMENTS WORK TO THE RESEARCH APPROACHES AND TOOLS

9.2.1 IMPROVEMENTS AT THE STRATEGIC LEVEL

That approach could be used to undertake an extensive exploration of an unrefined solution space and so could be used to research for future concepts, such as for SSH(N)s. Furthermore, the NPF approach could be further validated if a more extensive investigation of the SSH(N) concept was to be undertaken. Such an investigation might readily start with a wide-ranging exploration of the unrefined solution space, using SUPERB to generate synthesised designs and with the NPF approach presenting a production of the refined solution space. Design solutions, advanced by using the NPF approach and subsequent analysis of design trends, could be used for ‘conventional’ concept exploration. The NPF approach could be further validated by demonstrating its adaptability in exploring other types of submarine concept than the SSH(N). This has already been partly explored considering SUPERB’s ability to incorporate knowledge of new equipment, while using the novel arrangement approach (Compartment X-Listing) with the thought experiment of a teleporting submarine. A more comprehensive investigation could start with mathematically modelling a submarine concept to demonstrate that the NPF approach is not specific to the SSH(N) concept on which the current research was focussed.

9.2.2 IMPROVEMENTS TO USGOT

The USGOT tool has been limited to evaluating a small set of specific UUV missions that were considered to be demanding and thus require a fleet of highly capable UUVs. It was observed that a wider exploration of the SSH(N) idea would be likely to consider more UUV missions. This, in turn, could mean that different measures of effectiveness (MOEs) might have to be devised to reflect the UUV fleet's effectiveness. An obvious additional mission that could be simulated using USGOT is that of mine countermeasures (MCM). Thus, the MOE devised for MCM could be driven by the rate of area coverage of UUVs, as this could then allow for the rate at which mines/unexploded ordinance (UXO). This, in turn, could be important for wider operations, such as prior to amphibious landings or maintaining clear shipping routes.

A sensitivity study could also be undertaken on the size or any other significant design characteristic of the UUVs used to perform specific UUV missions. The simulations described in Chapter 3 used three types of UUV and attributed to the UUVs characteristics that were considered conceivable but not necessarily currently achievable. Particular attention is likely to be required to be paid in any follow-up usage to the design of the large Category A UUV/MUVs. Identifying a large Category A UUV/MUV that could seen to be realistic would provide confidence in the information provided to SUPERB regarding an SSH(N)'s UUV payload, stowage and LARS.

A further literature survey than the one presented in Appendix B Section B.1 on likely UUVs and UUV LARS could improve the assumptions made regarding this developing technology. Such improvement ought to better inform on the overall payload impact and composition indicated by USGOT, should SSH(N)s be investigated in the near future. This, in turn, could better inform the SSH(N) designer on the trade-offs between the size of the UUV payload (and supporting equipment) and submarine design impact that is driven by desired UUV capabilities.

9.2.3 IMPROVEMENTS TO SUPERB

9.2.3.i The Mathematical Modelling Module of SUPERB

The Mathematical Modelling Module of SUPERB has been limited by the range of equipment and physical features that it has been programmed to consider and the data inputted. Of particular relevance in this regard is the range of pressure hull configuration into which compartments are placed. Currently, SUPERB can only consider single or twin pressure hulls (side-by-side) with constant diameters. Historically, there have been a few attempts at multiple pressure hull configurations (see Sub-subsection 8.3.4.i). The mathematical representation of pressure hull geometry and configuration is currently hard-coded into SUPERB and any reprogramming would therefore require an in-depth understanding of the construction of SUPERB. Furthermore, extensive testing (and probable debugging) would be required to give assurances this additional modelling ability could then be used for further design exploration.

SUPERB was designed to be adaptable because of its ‘open’ nature and the inherent accessibility of its MATLAB code. Design validation studies ought to be undertaken to appreciate SUPERB’s flexibility. Some indication of its ability to accept modification was shown in the recreating in Section 5.4 of BMT’s SSGT submarine concept. The extent to which the SUPERB tool can be modified, and hence explore different concepts, would be useful in appreciating its potential as a research tool.

The Mathematical Modelling Module is limited by the data and knowledge needed to construct it. If SUPERB was to be used for a specific actual concept investigation, then it would be necessary to program in as much reliable data and knowledge as appropriate, to ensure the widest possible exploration of the unrefined solution space. This implies there ought to be an extensive preliminary investigation into what data and knowledge is available prior to using SUPERB for an actual exploration. This could then be used to construct a new Mathematical Modelling Module in SUPERB, and to generate system groups that reflect a wide diversity of possible concept designs for the new proposal. The collected data would need to include the cost of items and a relevant MoTPC devised.

9.2.3.ii The Arrangement Approach used by SUPERB

What was termed the ‘logistical effort’ was put forward in Subsection 4.5.2 to address the Style Preference issue, in encouraging adoption of submarine arrangements with features of ‘good’ style. These could include a more realistic modelling of personnel movement covering a series of pathways in the vertical and longitudinal directions (i.e. along decks and up/down ladders). It would have to address the possibility of such routes through a submarine being infeasible (e.g. personnel cannot traverse straight through a nuclear reactor, but instead, uses the access tunnel). A model of realistic distances between compartments could be constructed to address the 'logistical effort'. This could be used to improve the compartmental arrangement by mathematically minimising, this 'logistical effort'. It is considered that this introduction of a realistic arrangement would almost certainly prevent the 'logistical effort' being readily (mathematically) optimised, and instead require a computationally demanding algorithm to search for a preferred layout solution, which could be demanding in computational effort and time. The trade-off between any improvements to the arrangement generated, based on minimising the 'logistical effort' and a likely significant increase in computational load should be conducted to see if adopting this would be worthwhile.

A sensitivity study could also be undertaken concerning the individual relationships between compartment types used in the calculation of the 'logistical effort', as a means of detecting design drivers. This, in turn, could inform the designer which relationships are key to generating superior (defined by some user-defined metric) arrangements for designs, such as during an exploration of the SSH(N) concept.

The packing stage of the Compartment X-Listing (third Arrangement Step, see Subsection 4.5.4) has so far only been executed with pressure hull(s) constructed with a fixed cylinder diameter. In addition, the end spheres of a pressure hull have been mathematically represented as flat ends (that correspond to modelled torispherical end) with the pressure hull end 'averaged out' compared to torispherical ends. Thus, the packing approach used by SUPERB cannot be said to be that representative in that respect. Further development work is needed so that the packing approach can address a wide range of pressure hull geometries, possibly by simply modelling volumes which are 'inaccessible' due to a waist of a pressure hull as additional 'void' compartments – as discussed in Subsection 8.3.4.ii. The packing approach currently uses a grid system to record which regions of the pressure hull volume are accessible and inaccessible due to already arranged compartments. Thus, it is considered that modifying this grid system to consider pressure hull geometries with varying diameters should be relatively straightforward. A further consideration of the packing approach might be the modelling of layouts that are not dependent on deck heights and vertical distributions being homogenous throughout the pressure hull(s). If heterogeneous deck heights are to be modelled in SUPERB, generating a layout is likely to become more complicated, because it would be harder to define the regions of the pressure hull in which compartments were to be arranged. However, the grid system could be modified to incorporate the possibility of heterogeneous decks.

The selection of constraints clearly affects the arrangements produced by Compartment X-Listing, and Duchateau et al. (2015) have observed that the evolution of successive generations of arrangement configurations can be guided by the selection of a set of constraints. However, in the current research, there has been little variation in the selection of Constraint Profile. Thus, the effects of selection could be further investigated to obtain an improved understanding into the influence of the Constraint Profile on the arrangements produced by the Compartment X-Listing approach. This is considered to be necessary to build confidence if a large number of novel concept designs, such as SSH(N)s, are to be generated by SUPERB in populating the unrefined solution space.

The external arrangement is currently determined after the internal arrangement has been generated. It is assumed that the external arrangement is driven by the internal arrangement. However, this is not necessarily so, for instance, the accessibility for maintenance of some external compartments, such as externally stored UUVs and associated LARS. But this would probably require additional development of the Analysis Module of SUPERB in being able to assess hydrodynamic flow, since launching and recovering UUVs using a LARS, is likely to be strongly influenced by the flow profile of an advancing SSH(N).

9.2.3.iii The Analysis Module in SUPERB

The inability of SUPERB to assess the influence of hydrodynamic flow around the hull and appendages to predict hydrodynamic performance has just been mentioned. The hydrodynamic characteristics of a concept design might be approximately predicted with the use of pre-calculated lookup tables in conjunction with some simplified hydrodynamic equations. SUPERB's Analysis Module could then inform the designer of the design implications affected by hydrodynamic considerations. This could be structured in a similar manner to the USGOT simulations 'plug-in' to SUPERB. However, the limits of such an approach might then be flagged up so SUPERB would then be a means of highlighting where further research might be required before commencing concept exploration.

Within the generation of an arrangement using Compartment X-Listing, it could be possible to perform an assessment of a submarine's hydrodynamics by undertaking a similar analysis to that used by Paramarine's submarine assessment tools. The hull could be modelled and characterised by series of parameters, such as length to beam ratio. Hydrodynamic performance could then be predicted by SUPERB using a series of lookup tables and interpolation. The inclusion of such an assessment could then have design implications as it affects how the Measure for Tradable Performance Metrics (MoTPC) calculation of the overall speed of the design.

SUPERB currently assesses the UPC of a design in UCL pounds. If SUPERB was to be used for examining and exploring a future submarine concept, a specific cost model could be incorporated instead of the one used in this academic research. Such a model is likely to address the Through Life Cost (TLC) of a submarine by modelling its operational expenditure as well as its procurement cost. A further aspect to be considered could be the cost consideration of a submarine force's size and composition, as well as the force's interaction with the rest of a military capability. For example, the reduced cost of equipment due to the economy of scale, or political realities demanding the use of nationally produced equipment.

9.2.4 IMPROVEMENTS TO THE NOTIONAL PARETO FRONT APPROACH

How acoustic signature strength and detection performance might be addressed at the concept level and reflected in the MoTPC concept of performance is outlined in Appendix G. The definition used by SUPERB for naval architectural balance could be extended to add in assessment of the likelihood of detecting a specific vessel exceeding the probability of the submarine being detected by that vessel. This, in turn, could be considered during the generation of the system groups and their SG-level Pareto Fronts – so that design choice could potentially include concept designs with superior signature and sonar performances in the performance metric.

It has been suggested to the candidate by Duchateau (2015) that a more targeted approach to generating unrefined potential solution solutions might be possible by interdependent SG-level Pareto Fronts being holistically considered (and not individually and sequentially). Currently, using the method outlined in Chapter 6, generating 'every' possible interdependent set of combined system groups would be computationally impractical as the number of possible combinations would likely be too high for (current) practical computational capability. A possible solution would be the adoption of genetic algorithms (outlined in Subsection 2.5.3) to generate an SG-level Pareto Front by identifying a set of non-Pareto dominated combined SG options for a combined SG-level Pareto Front. Instead of 'blindly' exploring all possible combinations of combined system groups, the genetic algorithm would 'learn' from the evolution of successive generations of combined SG-level Pareto Fronts, which were options for the combined non-Pareto dominated (and feasible) system groups. This would help improve the pool of potentially unrefined potential design solutions used to generate the Balanced Pareto Front, by further focusing the design options towards the Balance Pareto Front (as proposed in Subsection 8.3.5). Research could be undertaken to explore the viability of this approach, possibly repeating the testing of designs described in Chapter 7 and comparing against the results presented in Chapter 7. As evidence of the viability of this improvement, genetic algorithms have already been seen to be highly effective at solving well-defined problems, e.g. van Oers et al. (2008). Genetic algorithms could be used to generate SG-level Pareto Fronts faster than the current approach of calculating 'every' possible SG option.

An additional development of SUPERB could include the ability to capture a selection of data and metadata, which could be analysed to provide information on implicit trends, such as the effect arrangement style could have on performance and cost at the early-stage of the Concept Design phase. This could be used in the analysis of the designs lying on the Balanced Pareto Front to inform further the designer when undertaking 'conventional' concept exploration. Another example of using metadata could be output from SUPERB, which could provide insights as to why a set of designs cannot achieve naval architectural balance. An 'analytical engine' subroutine (proposed in Subsection 8.3.5) could be produced to recognise why a particular set of inputs failed to achieve naval architectural balance. This should be relatively straightforward using error codes in the Analysis Module of SUPERB (outlined in Table D5 in Appendix D Section D.7.5). The 'subroutine' could flag up specific regions of the unrefined solution space, which were considered likely to contain the unrefined potential solutions and that SUPERB could subsequently synthesise. This would make a more efficient use of computational resources, and ultimately time. The proposed ‘analytical engine’ subroutine in the Analysis Module might even be made able to update dynamically the pool of unrefined potential solution options as it ‘learns’ and, by sampling a smaller region of unrefined solution space, might be shown to increase the statistical confidence that the region could be more accurately modelled. This would be due to a higher proportion of the design options in the refined solution space being sampled.

9.3 FURTHER INVESTIGATIONS USING THE PROPOSED APPROACHES AND TOOLS

9.3.1 USE OF THE COMPARTMENT X-LISTING APPROACH

The Compartment X-Listing approach might be applicable to naval surface ships, such as combatants, particularly with regard to the arrangement of compartments. Given SUPERB uses the Compartment X-Listing approach to generate conceivable but not 'optimised' arrangements, such a SUPERB (ship) tool could potentially be used to explore early-stage concepts in a similar manner to that proposed to novel submarines.

Given the compartments in the superstructure of a naval surface ship will strongly influence the internal arrangement and vice versa, it is not yet apparent how the presence of a superstructure can be reflected in a surface ship version of SUPERB. The relationship between arrangements of compartments on decks inside the hull and the upper deck and above would need further investigation. Any version of Compartment X-Listing would have to take into account other layout constraints, such as the position of main armament, communications, and machinery up/downtakes. Thus, an entirely new Constraint Profiles would be required, not least because ships and submarines typically have markedly different operational requirements. For example, because ships operate on the surface and are thus exposed to waves more than submarines, the arrangement of compartments to promote superior seakeeping performance would be an important new Style Preference (in the first Arrangement Step outlined in Subsection 4.5.2).

9.3.2 USE OF THE NOTIONAL PARETO FRONT APPROACH

The proposed NPF approach should not only be applicable to early stage submarine concept design but also to a range of alternative applications, such as naval surface vessels. In theory, any synthesised complex system (such as a submarine) comprising multiple subsystems could be receptive to the approach if the necessary criteria are able to be met. These criteria would include a sufficient understanding of the systems groups and the operational relationships between each system group. Knowledge of how systems are synthesised to generate the whole system would also be necessary. Such criteria would allow the SG-level Pareto Fronts to be calculated, in conjunction with appropriate schemes for evaluating the synthesised complex system's performance and cost.

A consideration of the wider operational environment could be included for the choice of top-level input variable value ranges (such as those in Table D1 in Appendix D Section D.2). For example, in the case of an SSH(N), this would guide how satisfactorily a design option 'fits' within the operational needs of the rest of friendly armed forces. For example, if an SSH(N) were to be part of a carrier protection force, the SSH(N) then needs to be able to transit at least at the same speed as the rest of the fleet.

9.3.3 IMPROVEMENTS IN CONCEPT EXPLORATION PRACTICE

The SUPERB tool could be used to perform random walk explorations of the design solution space, which might have potential as an alternative method of guiding the exploration of novel submarine concepts. This alternative approach is considered to be more practicably applicable if a preferred design (or set of designs) has already been determined, and thus, the solution space has been focussed. Hence, such explorations could be performed following the execution of the NPF approach and production of concept designs from the Balanced Pareto Front. A trial execution of this random walk solution exploration could then be undertaken. It might confirm that the output from the execution of a particular exercise NPF was worthwhile as a means of investigating a novel concept.

A random walk exploration could be undertaken by randomly (unbiasedly) varying the value of a single top-level input variable (such as maximum speed and deep diving depth) within a pre-set range from a baseline design point and using SUPERB to synthesise a new design solution, which becomes a new baseline design point. Each new design would represent a 'step' in the random walk exploration through that particular solution space. The random unbiased nature of the walk should then mean that (probabilistically) all the new design options cluster around the original baseline design. These design options could then be analysed to narrow further down the preferred solution design for a new concept; by carrying out the second stage of the procedure outlined in

Figure 3 in Subsection 1.3.2 (Page 26). This requires the designer to decide that the assumptions have not been violated and the incremental steps are not meaningless given the granularity of the error budget.

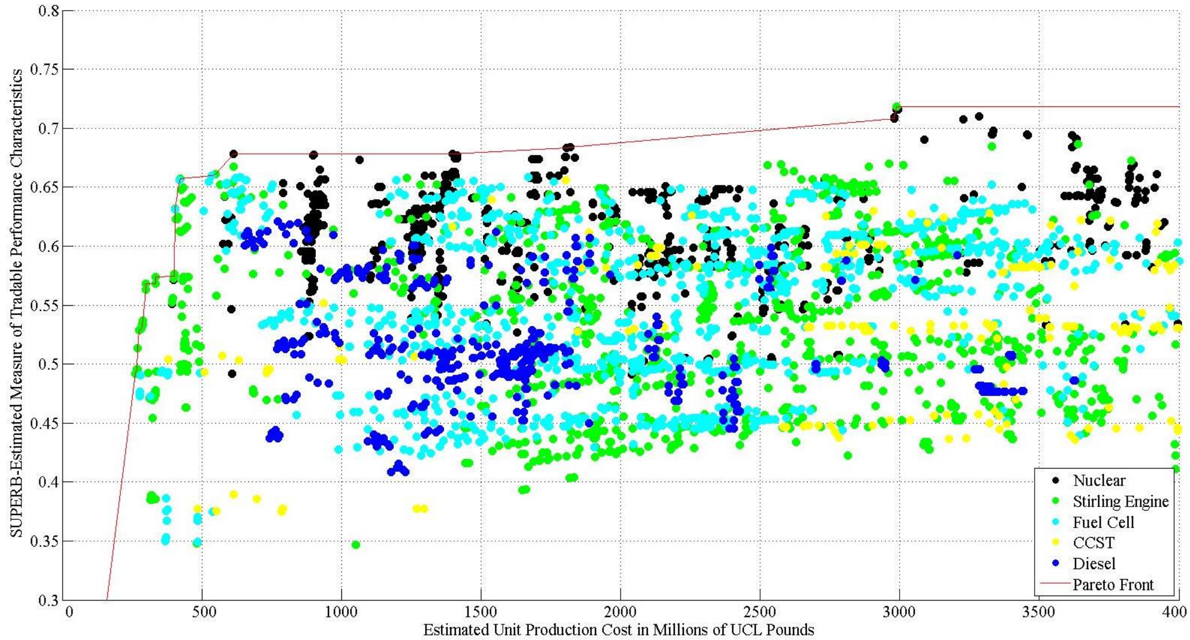

Figure 39 – Demonstration of Using SUPERB to Explore Preferred Primary Power Selection

Figure 39 shows the result of a demonstration of a possible analysis that could be undertaken using designs generated from SUPERB. In Figure 39, approximately 10,000 (unrefined for demonstration purposes) submarine design points have been randomly generated using a random walk exploration to illustrate how (in this instance) an examination of primary power selection could be carried out. Following the execution of the NPF approach, the Balanced Pareto Front could be constructed (for demonstrative purposes[1] said to be the red line in Figure 39) and subsequent analysis performed. For example, from this demonstration, it can be seen that for cheaper submarines (less than a UPC of circa 600 million UCL pounds compared to a baseline of £1 billion for the UCL 5000 tonne SSN outlined in Appendix H Section H.1) that Stirling engines are seen to be preferable for primary power selection

[1] It would have been computationally impractical to generate 10,000 balanced designs for this demonstration. Thus, for illustrative purposes only, the designs and the Pareto Front in Figure 39 are notionally considered balanced. The results from this demonstration should not be used in any submarine research.

rather than the nuclear plant assumed for an SSH(N). For more expensive boats, nuclear power is indicated as the preferred technology for primary power selection.

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APPENDIX CONTENTS

APPENDIX A - UUV LARS AND STOWAGE IDEAS

A.1 INTRODUCTION

The Launch and Recovery System (LARS) and storage configuration selected for UUVs could have an impact on the design of an SSH(N). The impact may include significant influence on the relative positioning of compartments in the arrangement and the total volume assigned to UUV hosting and support. Two storage options to host larger Category A UUV/MUV have been conceived to provide SUPERB with greater scope for the variation in generated arrangements.

The development of a LARS was considered outside the scope of this thesis research as other organisations are already focusing on LARS development, especially concerning the LAR and storage of a few smaller UUVs. Two novel LARS solutions for multiple UUVs (as per the outcome of the USGOT simulation results) have been proposed by Purton et al. (2013b) to help explore if such a LARS might be possible.

A.1 CURRENT LARS

The launch and recovery (LAR) of a UUV from a submarine is a complex problem that has been widely discussed in a number of papers, for example by Geleff et al. (2012) and Binns et al. (2011). The most challenging aspect is the recovery phase for which the technical challenges are significant. The UUV and host vessel must be able to locate each other within the stealth constraints of a mission, and the UUV must then negotiate complex hydrodynamic conditions and be recovered into the submarine without damaging either the UUV or placing the SSH(N) at risk.

A number of methods of UUV launch and recovery have been studied to a concept level, and a small number of systems are in development for which the details are available in the public domain. One example is the use of existing submarine equipment, such as the 21-inch torpedo tube. This has been discussed in depth by Geleff et al. (2012) and a similar system for the SUBROV ROV has been demonstrated by Saab (2014). This method provides a distinct advantage, in that it makes use of existing submarine equipment and operational experience to launch, recover and stow the UUVs, and, therefore, provides a potential option for retrofitting a limited UUV LAR capability to existing vessels. The disadvantage, however, is that it limits UUVs to the 21” diameter of torpedo tubes used by most major navies. It is considered that 21” torpedo tubes would only be suitable for Category B and C UUVs. Additionally, the bow of the submarine might not be the ideal location for recovery, as the bow typically contains the bow sonar and torpedo stowage and tubes. This makes it a less attractive solution for a future SSH(N) if larger UUV/MUVs are also to be hosted and launched and recovered.

Other options, which consider a wider variation of UUV, have received less attention. One such system under development is the Special Launch Tube, which will be included on the new Swedish A26 submarine (Saab, 2015) and has a diameter of 1.5 metres. This system allows recovery and stowage of larger UUVs (which should encompass most Category A MUV/UUVs). Ideally, the UUVs would be recovered to a dry[1] space so they can then be accessible for maintenance and data transfer by personnel. The A26 design, however, only calls for a few larger UUVs and not a significantly large UUV payload such as that suggested by the simulation results using USGOT (see Chapter 3).

A.2 PROPOSED LARS ARRANGEMENT SOLUTIONS FOR SSH(N)S DIFFERENT CONFIGURATION OPTIONS IN SUPERB

SUPERB has three different configuration options for the stowage of the larger Category A UUVs. They can be located external to the pressure hull, which entails all the stowage and LARS equipment located being outside the easily assessable pressure hull. Alternatively, all the UUV storage and LARS equipment can be placed internal to the pressure hull. A third option is for the UUVS and the LARS to be located externally to the pressure hull, with an internally located ‘garage’ to perform maintenance on a small portion of UUVs. It is considered that there would be design trade-off between external and internal UUV location, if a SSH(N) was actually designed. External location would remove a demand on the internal volume provided by the pressure hull, but could also increase the risks to UUV availability due to UUVs being more inaccessible. The third option listed here is intended to be a ‘halfway house’ between fully internally and externally located UUVs.

[1] The term ‘dry’ refers to location being internal to the pressure hull. The term ‘wet’ is for external location to the pressure hull.

A.3 "SINGLE INTERFACE" LARS ARRANGEMENT SOLUTION

Should the SSH(N) need to handle a significant number of Category A UUV/MUVs (as suggested by the simulation results in Chapter 3), the SSH(N) should be designed with consideration towards handling and storing Category A UUVs. Two philosophies are proposed for the means of launching and recovering the UUVs. The first is a system whereby the UUVs are housed in a central storage area, and then deployed and recovered from a single interface to the external environment. The benefit of this approach is that it could minimise the volume required for storage and the interface to the external environment.

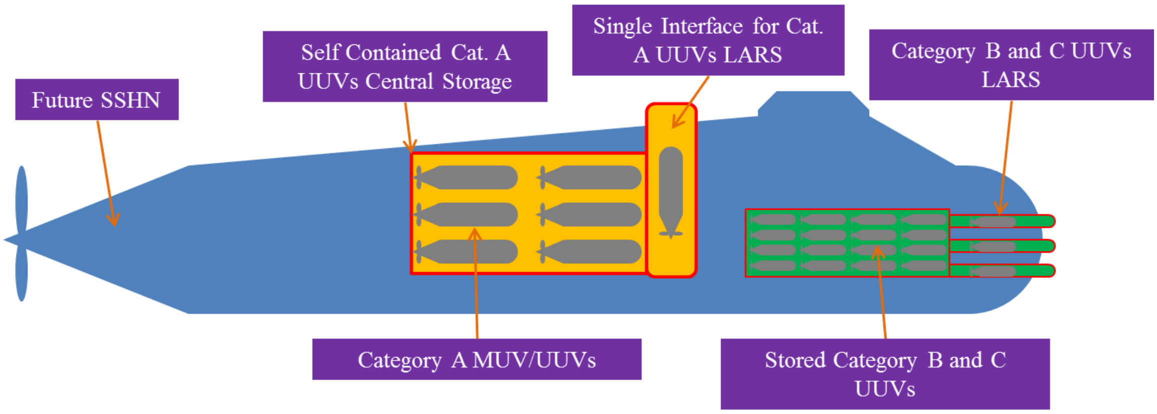

Figure A1 – Topology of "Single Interface" LARS for Category A UUV/MUVs in an SSH(N)

An example of this topology is shown in Figure A1. The disadvantage is that it would rely heavily on the interface between the pressure hull and external environment to be reliable, and a malfunction or blockage in this interface may affect the UUV LAR capability. The size of the centralised storage arrangement would also be a challenging system to achieve, considering the degree of handling that will be required to stow the different types of UUVs and transfer them to and from the interface mechanisms.

A.4 "SELF-CONTAINED" LARS ARRANGEMENT SOLUTION

Another proposed approach is for the Category A MUV/UUVs to be stowed, launched and recovered from their own individual tubes, each with a self-contained launch and recovery device. This is depicted in Figure A2. An approach similar to that taken on the US Navy SSGN (United States Navy, 2014) submarine conversions could be utilised. In this instance, the arrangement of tubes would be used to provide a compact means of storing large UUVs, while also improving reliability in that a failed launch and recovery device might only result in losing one UUV or one tube set.

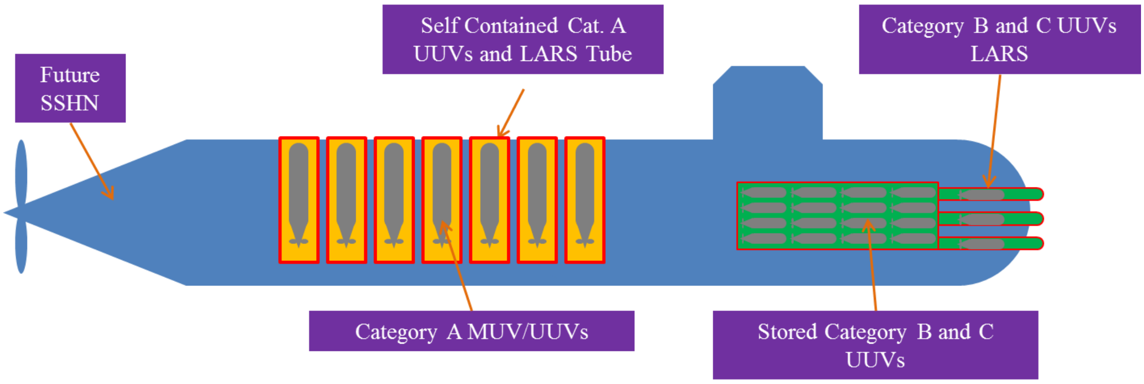

Figure A2 – Topology of "Self-Contained" LARS for Category A UUV/MUVs in an SSH(N)

It is considered that the proposed LARS might be similar to Bluefin Robotics/Battelle's "SSGN platform concept" idea (Granger, et al., 2012). This would be complemented by a system such as a bespoke LARS or a variation of a Special Launch Tube to deploy Category B and C UUVs.

A.5 LARS CONCEPTS

A.5.1 INTRODUCTION

The methods of launching and recovering single UUVs is outside the scope of the main thesis, however, here concepts for multiple launchers of UUVs are proposed to explore how such handling systems might be designed. The designs are at the sketch stage and are intended as generic LARS and thus may be suitable for handling larger Category A UUVs or only smaller Category B and C UUVs.

A.5.2 PROPOSED HANDLING SYSTEM #1

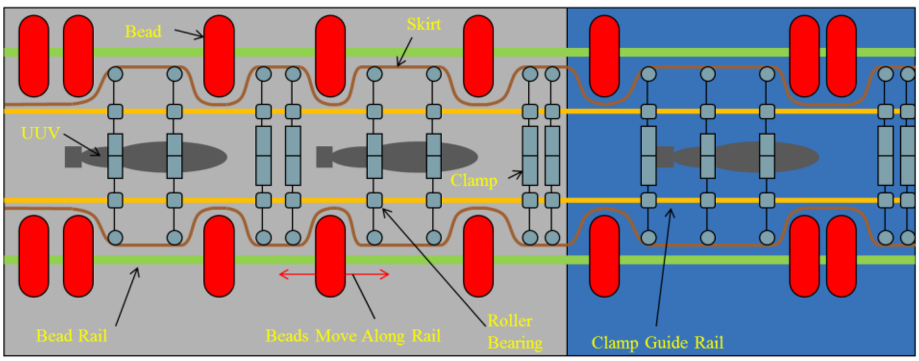

Figure A3 – Sketch Design of Proposed Handling System #1

Based on the many examples in nature of peristaltic locomotion (Encyclopaedia Britannica, 2015), beads would be driven along a rail using a system of electromagnets to drive the UUV support frames along guide rails. The frames move linearly along a guide rails with roller bearings supporting the frames. A skirt would be used to separate the beads and driving rails in a dry environment and the wet environment at only shallow depths. This is depicted in Figure A3.

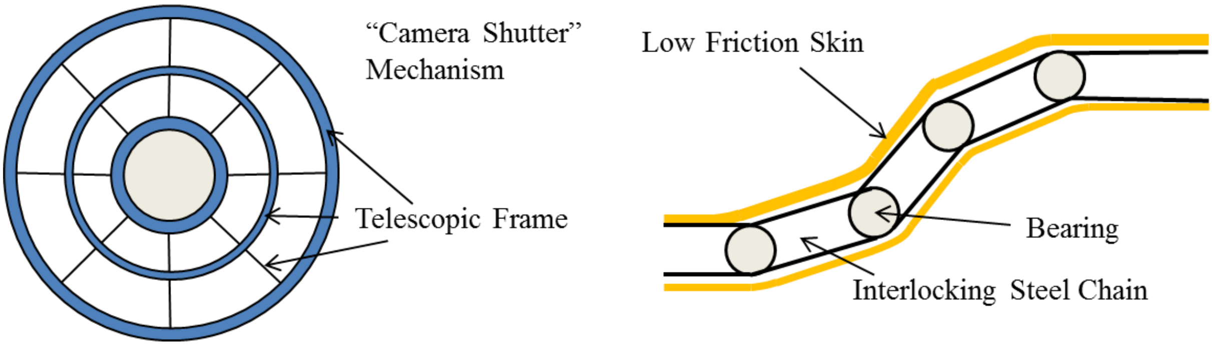

Figure A4 – Design of Clamp and Skirt for Handling System #1

The skirt would be comprised of a low friction flexible skin to allow the bearings on the beads and frames to travel easily across it and a steel chain akin to a bike chain, which provides rigidity and strength (shown in Figure A4). The support frame would be designed to be able to increase the circumference of the inner circle that would grip onto the UUV (again shown in Figure A4). By widening the circumference, it would decrease the effect of the orientation of the UUV during capturing. The telescopic frame dimensions would be manipulated by electric actuators, with the ability to increase the circumference of the inner ring to aid in UUV capturing. It too would be manipulated by electrical actuators. It is foreseen that the skirt may not be able to withstand the very high pressure from operating at depth and thus this system may be limited to shallow operations in the littoral, or two hatches and a lock-in lock-out chamber might be required.

During LAR very low SSH(N) velocity (2-3 knots) could make coordinating the UUV and LARS connection much easier, since the SSH(N) having forward velocity should allow the hydroplanes to maintain a constant trim – improving the chances of a successful capture of the UUV. Most UUVs currently have a limited sprint speed of typically 6 knots. Thus, the SSH(N) should not move any faster as it would be difficult for the UUV to catch up and make a second attempt after a failed capture.

Furthermore, the increased velocity could make the flow field of the adjacent seawater unfavourable (i.e. turbulent) with regards to UUV capture.

A.5.3 PROPOSED HANDLING SYSTEM #2

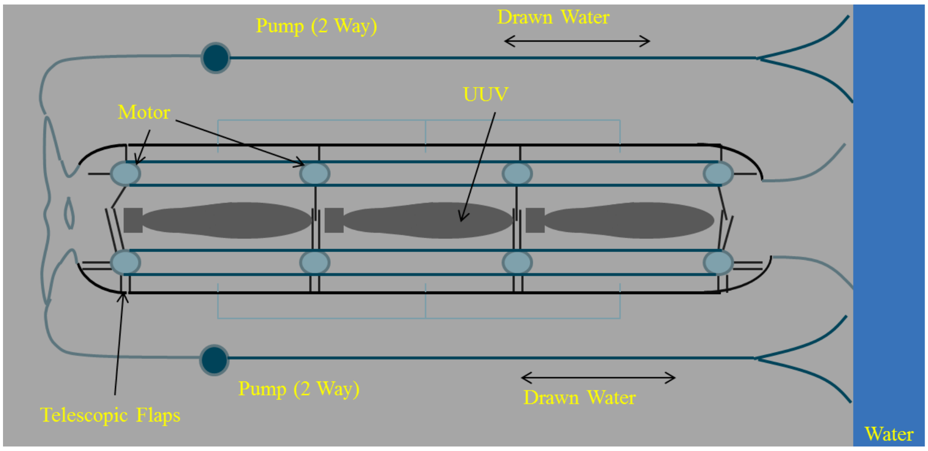

Figure A5 – Sketch Design of Proposed Handling System #2

This concept illustrated in Figure A5 utilises a series of electrical motors to power a conveyor system that launches and recovers the UUVs externally to the pressure hull. The UUVs would always be in wet conditions and so the electrical motors would be separate in dry conditions. The UUVs should float in the launch tube and held in place with high friction pads so they do not move about relative to the SSH(N) during manoeuvres. The conveyor belt would have spring-loaded flaps as no powered actuation is seen to be necessary. They would have a high stiffness to displace the UUVs during LAR. The system could be designed so that it could work at all depths and not just at shallow littoral depths. A two-way pumping and valve system would be needed to equalise pressures while launching recovery given the water pressure inside and outside the launch tube could be different. The pumping system would also have to replace/withdraw water from the rear of the launch tube during launching/recovering. A pressure equalisation system would be likely to be required for the different sections of the conveyor belt on the 'return' side to deal with the pressure difference during LAR. During recovery, guides could be deployed outside the casing of the SSH(N) (not shown in Figure A5) to position the UUV into the LARS.

APPENDIX B - SUPPORTING 'THEORY' NOTES FOR USGOT

NOMENCLATURE

A	Bluff body area of the UUV [m^2]
C_d	Coefficient of Drag
D_{UUV}	Diameter of a MUV/UUV [m]
$D_{Cat\ A\ UUV}$	Diameter of a Category A MUV/UUV [m]
ET	Endurance Time (Hours) (Time a UUV is On-Station, See USGOT in Chapter 3)
E_{Total}	Total energy stored onboard a UUV [Joules]
K_1	Collection of terms that have been repeated on multiple occasions in the whole equation for USGOT's "Payload Calculator"
$L_{Cat\ A\ UUV}$	Length of a Category A MUV/UUV [m]
LR	Loss Rate (of UUVs Performing a Mission)
L_{UUV}	Length of a MUV/UUV [m]
MT	Maintenance Time [Hours] (Time a UUV takes for recharging, maintenance and data transfer)
n	Number of (Real) Nodes in a Polygon Set
N_s	Total Number of UUVs on station (for that UUV Category)
N_T	Total Number of UUVs (for that UUV Category)
N_{UUV}	Number of UUVs Recharging/Refuelling (for that UUV Category)
P_{eq}	Equivalent Probability of Detection of a Target by a 'Virtual Node'
Q	The Probability of Non-Detection of a Target
r	Radial Distance
ReN	Real Node (i.e. An On-station UUV).
ROO	Radius of Operations [nm]
SRe	Sprint Reserve [%] (Reserve of Energy Stored on a UUV, See Appendix B on USGOT Construction)
SR_n	Sensor Range of Node [nm]
SR_n'	Equivalent Sensor Range of Virtual Node [nm]
TD	Transit Distance [nm]
TD_{max}	Maximum Transit Distance [nm]
TD_{min}	Minimum Transit Distance [nm]
TrT	Transit Time [Hours]
TS	Transit Speed [Knots]
TS_{max}	Maximum Transit Speed [Knots]
TS_{min}	Minimum Transit Speed [Knots]
TS_{opt}	Transit Speed to achieve maximum UUV range [Knots]
u	Displacement squared of a node in the spatial vector: x (See Notes on USGOT Construction in Appendix B)
$\vec{U}$	Displacement Vector (For Nodes in a FEA Mesh)
VN	Virtual Node (Virtual 'UUV') in effect a 'source' of probability.
α	Ratio between Transit Speed and Optimum Speed for Maximum Range

φ Product of the number of UUVs on-stations (of that type of UUV) and the transit distance (TD) (See USGOT in Chapter 3)

B.1 PAYLOAD CALCULATOR CONSTRUCTION SOURCE DATA FOR UUVS

A function in MATLAB called the Payload Calculator was created to calculate the 'optimum' trade-off between different UUV characteristics, such as transit speed, to supply USGOT with 'optimum' numbers and transit distances for a SSH(N)'s UUV payload. Appendix B covers the development and construction of the Payload Calculator. Table B1 lists the characteristics of actual UUVs, which have been used to create the Payload Calculator.

Table B1 – UUV Datasheet Used in Constructing the "Payload Calculator". N.B. Estimates Used where No Data Was Available

Manufacturer	Vehicle	Date	Length (m)	Diameter/ Width (m)	Max. Area (m^2)	Max. Depth (m)	Weight (kg)	Stored Energy (kWh)	Max Speed (kts)	Max Endurance (hr)	Speed for Max Range (kts)	Max Range Time (hr)	Max Range (km)
ISE	ARCS	Jan-84	6.4	0.69	0.37	304.8	1360.8	20	5.5	10	4	n/a	n/a
ISE	Explorer (3x Battery Bank)	Feb-04	6	0.74	0.43	5000	1250	1.6	5	240	4	13.5	100
ISE	Theseus (AgZn Battery)	May-95	10.7	1.27	1.27	2000	8600	600	5.5	60	4	184	1363
ECA	Asemar	Jul-10	5.7	0.7	0.38	300	1130	25	7	15	4	n/a	n/a
ECA	Daurade	Sep-08	5	0.7	0.38	300	950	22	8	10	4	10	74
GESMA	Redermor-1 (High Speed Version)	Jun-99	5.5	1.03	0.83	200	3100	62	10	7	5	7	65
Atlas	SeaWolf A	Jul-07	2	0.5	0.08	300	112	n/a	8	3	4	n/a	n/a
Atlas	Sea Otter Mk1 (NiHM Battery)	Apr-04	4.5	1.2	0.57	600	1500	36	5	15	3	15	83
Atlas	Sea Otter Mk2	Jun-10	3.45	0.98	0.38	600	1100	36	8	24	4	24	178
Diehl BGT	DAVID	May-08	2.8	0.3	0.07	n/a	250	n/a	n/a	n/a	4	n/a	n/a
Hafmynd	Gavia (Defence)	Apr-11	1.7	0.2	0.03	1000	62	1.2	6	8	3.5	32	207
Daewoo	OKPO 300	Jan-06	1.8	0.26	0.05	300	55	n/a	6	10	4	n/a	n/a
Daewoo	OKPO 6000	Jan-97	3.8	0.7	0.38	6000	950	n/a	3	10	3	10	56
Uni. Of Tokyo	Manta-Ceresia	Jun-97	0.489	0.634	0.22	1.5	13.8	0.094	2	2.5	2	2.2	8
Kongsberg	Hugin 3000	Jun-00	5.5	1	0.79	3000	1400	45	4	60	4	60	444
Kongsberg	Hugin 4500	Jul-06	6	1	0.79	4500	1900	60	4	60	4	60	444

Manufacturer	Vehicle	Date	Length (m)	Diameter/ Width (m)	Max. Area (m^2)	Max. Depth (m)	Weight (kg)	Stored Energy (kWh)	Max Speed (kts)	Max Endurance (hr)	Speed for Max Range (kts)	Max Range Time (hr)	Max Range (km)
Kongsberg	Hugin 1000 (3000m variant)	Apr-11	5	0.75	0.44	3000	850	15	6	24	4	18	133
SAAB	AUV 62 ASAT	Jan-08	3.5	0.533	0.22	300	620	25	12	12	4	12	89
BAE	Talisman M	Mar-08	4.5	2.5	2.75	300	1000	57.6	5	24	4	24	178
BAE	Talisman L	Jun-09	1.4	2.5	2.75	300	50	n/a	5	12	4	12	89
Nat. Oceanography Centre	Auto sub 3	n/a	5.5	0.9	0.64	1600	2300	n/a	4	150	4	150	1111
Nat. Oceanography Centre	Auto sub 6000	Jul-08	5.5	0.9	0.64	6000	1500	n/a	4	36	4	36	267
Boeing	Echo Ranger (Osiris)	Jul-06	5.5	1.27	0.00	3050	5308	875	8	28	4	28	207
Bluefin	Bluefin 9 / Sea lion 2	Jul-10	1.75	0.24	0.05	200	60.5	1.5	5	12	4	12	89
Bluefin	Bluefin 12 Deepwater	Jul-10	4.3	0.32	0.08	1500	259	7.5	5	24	4	24	178
Bluefin	Bluefin 12 Base	Jul-10	2.31	0.32	0.08	1500	113	7.5	5	44	4	44	326
Bluefin	Bluefin Spray Glider	Jul-04	2.13	0.2	0.03	1500	52	4.86	0.7	4320	0.4	5720	4237
Bluefin	Bluefin 21 (Muscle)	Jun-10	3.5	0.533	0.22	200	425	13.5	5	5	3	5	28
Bluefin	Bluefin 21 (BPAUV)	Jun-03	4.93	0.533	0.22	200	357	7	4	18	4	18	133
Hydroid	Remus 100	Feb-12	1.6	0.19	0.03	100	37	1	6	22	3	22	122
Hydroid	Remus 600	Feb-12	3.25	0.32	0.08	3000	240	5.2	5	70	4	70	519
Hydroid	Remus 6000	Mar-12	3.8	0.7	0.38	6000	860	11	5	22	3.5	22	143
NUWC	Manta	Jul-99	10.44	4.72	10.82	243	14060	128	10	5	5	5	46
Columbia Group	Proteus (Dual Mode Underwater Vehicle)	Sep-11	7.42	1.6	2.01	45.72	3737	296	10	950	1.5	342	950
Penn. State Uni.	Seahorse 1	Oct-00	8.66	0.97	0.74	1000	4793	166.183	6	125	4	100	741
Teledyne Webb	Slocum (L)	Jun-11	1.5	0.22	0.04	1000	54	n/a	0.68	5720	0.35	5720	3708

B.2 DERIVING EQUATIONS FOR THE PAYLOAD CALCULATOR

B.2.1 PAYLOAD TO TOTAL NUMBER (NT) OF UUVS FOR A SPECIFIC UUV CATEGORY

Finding the total number of UUVs from a payload (P) volume (taken to nearest integer rounded down as obviously cannot have a fraction of a UUV):

$$N_T = \left\lfloor \frac{P}{VD} \right\rfloor \qquad \text{[Eqn. B1]}$$

B.2.2 TRANSIT TIME – TrT

The transit time (TrT) from SSH(N) to Station (or the other way):

$$TrT = \frac{TD}{TS} \qquad \text{[Eqn. B2]}$$

B.2.3 TRANSIT TIME – TS

Transit can be expressed as a multiple of TS_{op} using the scaling factor α_t:

$$TS = \alpha\ TS_{opt} \qquad \text{[Eqn. B3]}$$

B.2.4 UUV RELATIONSHIP TO ENERGY EQUATIONS

For the displacement of a single UUV, it is assumed that it is linearly proportional to the ratio of amount of stored energy (E_{Total}) to coefficient of drag (C_d):

$$\left(\frac{E_{Total}}{C_d}\right) \propto VD = c_1\ VD \qquad \text{[Eqn. B4]}$$

For the relationship, a further assumption had to be made that any UUV used in the Payload Calculator has a good hydrodynamic shape (as opposed to box-shaped UUVs). Considering the likelihood that any deployed UUV would have to traverse a significant distance of tens or hundreds of nautical miles, this was considered a reasonable assumption. Evidence of this relationship assumed in Eqn. B4 can be seen in Figure B1. The strong correlation (R^2=0.69) giving a high degree of confidence that this relationship assertion is valid. The value of the proportionality constant is 0.916 [kWh/kg], which is equal to 3,296,700 [J/kg] since SI units are used throughout the equations for the Payload Calculator. The value was taken from the UUV characteristics plotted in Figure B1. This essentially represents the current level of energy storage technology for UUVs.

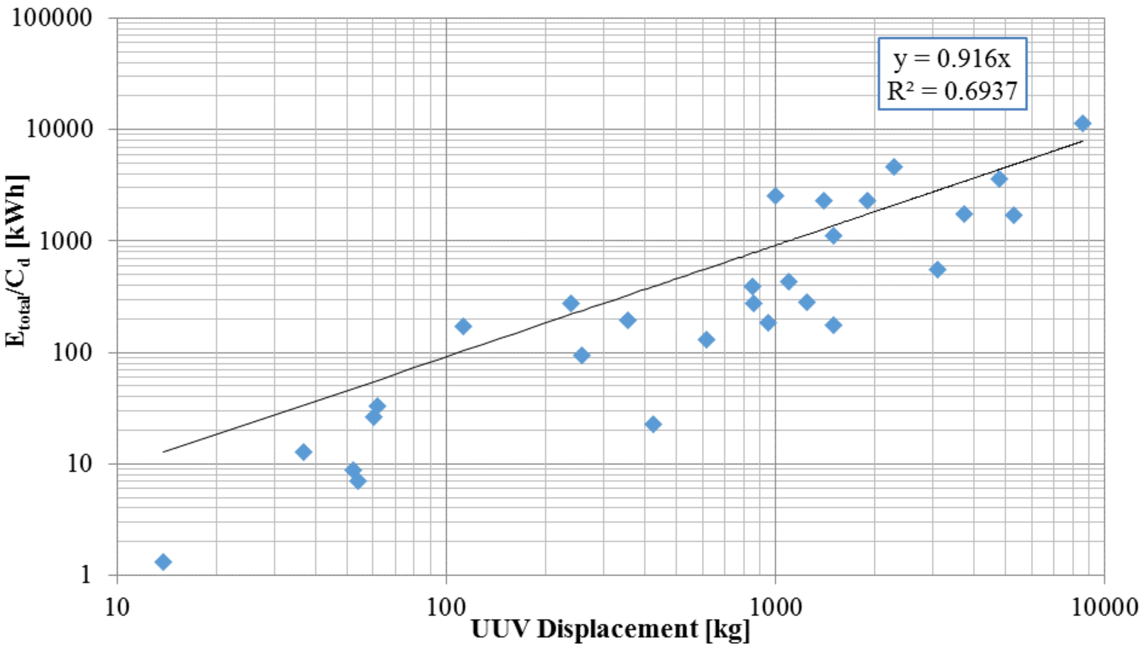

Figure B1 – Relationship between E_{total}/C_d and UUV Displacement

It was found in the UUV survey (Table B1) that the majority of UUVs have a similar transit speed (approximately 4 knots) for similar ranges and maximum dive depths. The samples of UUVs in Figure B1 contain UUVs from approximately the last two decades and hence some UUVs do not reflect improvements in energy storage and propulsion technology. This, along with variations in casing shape, range, transit speed and maximum diving depth was the reason the correlation coefficient is not higher. For instance, if the relatively very small (13.8 kg) Slocum (L) UUV were removed – as it is a super long-range glider – the correlation in Figure B1 would improve.

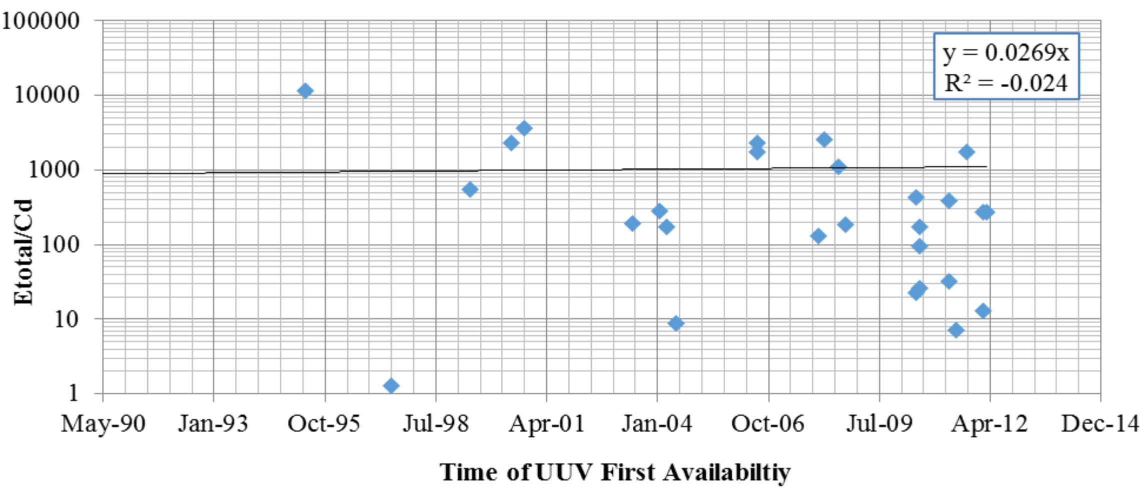

Figure B2 – Linear Relationship between Total Stored unit to Coefficient of Drag Ratio and Time of UUV (Hydrodynamically Shaped) First Availability

Figure B2 shows the ratio between E_{total} to C_d for UUVs indicates that UUVs have not followed a statistically strong trend for the E_{total} to C_d ratio over the last 20 years, and thus it was assumed that the relationship shown in Figure B1 to be time invariant.

B.2.5 PROPULSION ENERGY (INCLUDING THE SPRINT RESERVE – SRe):

Total energy has been modelled as the sum of the hotel load and energy for propulsion:

$$\text{Total Stored Energy} = E_{Total} = \text{Propulsion Energy} + \text{Hotel Energy} \qquad \text{[Eqn. B5]}$$

Thus:

$$\text{Total Power of UUV} = P_{Total} = \text{Propulsion Power} + \text{Hotel Power} \qquad \text{[Eqn. B6]}$$

The total transiting time back and forth from being on-station to recharging is twice the transit time (TrT). In addition, any increase in velocity will necessitate the expended propulsion energy to be increased by a power of three. This provided a basis to construct an equation for propulsive power:

$$\text{Propulsion Power} = 0.5\rho A C_D (TS \times SRe)^3 = 0.5\rho A C_D \eta^{-1} (\alpha\ TS_{opt} \times SRe)^3 \qquad \text{[Eqn. B7]}$$

It was assumed the propulsive power was only required for transiting with any energy expended for propulsion. When a UUV is on-station, the velocity is zero and it was assumed that any energy needed for repositioning would come from the sprint reserve (SRe). The efficiency of the propulsion system (η) was also taken in account during the calculation of the propulsion energy.

$$\begin{aligned} \text{Propulsion Energy} &= 0.5\rho A C_D \eta^{-1} (TS \times SRe)^3 (2\ TrT) = 0.5\rho A C_D \eta^{-1} (TS \times SRe)^3 \left(2\frac{TD}{TS}\right) \\ &= 0.5\rho A C_D \eta^{-1} \left(\alpha\ TS_{opt}\ SRe\right)^3 \left(2\frac{TD}{\alpha\ TS_{opt}}\right) \end{aligned} \qquad \text{[Eqn. B8]}$$

Eqn. B7 advanced a relationship between the displacement of UUVs and the bluff body area (A) of the vehicle. The propulsion energy equation hence is sensitive to any change in value for the area. The relationship has been explored using the existing UUVs and the results are shown in

Figure B3.

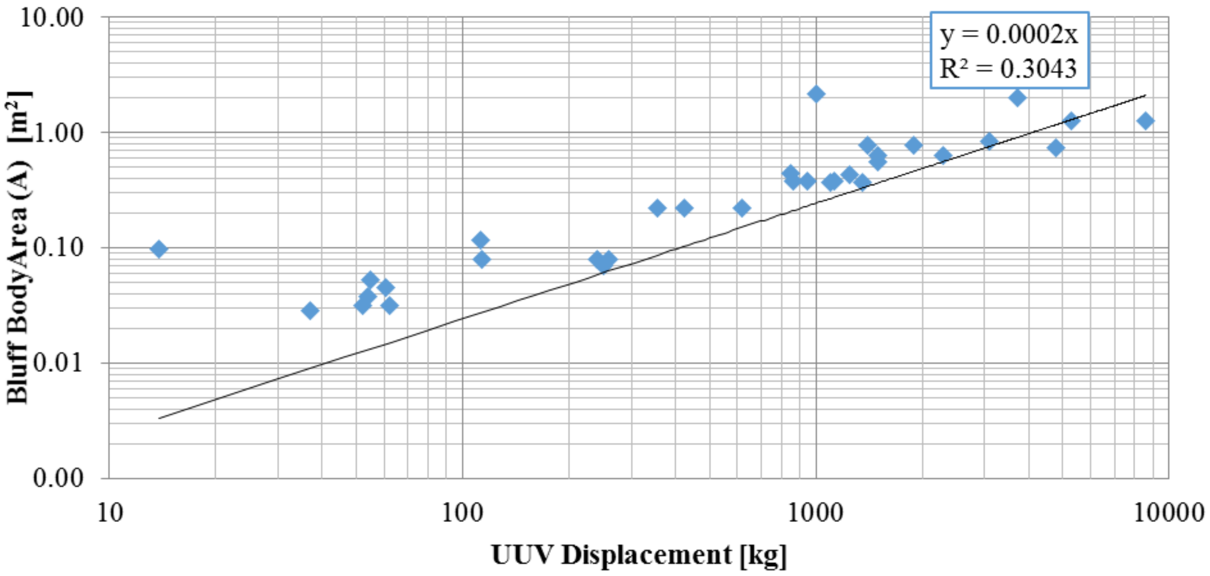

Figure B3 – Relationship between Maximum Cross-Sectional Area and Weight of UUV (When Hydrodynamically Shaped)

The correlation in

Figure B3 is not very strong (although still significantly strong to meet a typical 95% certainty of correlation criterion). Thus, if the bluff body area (A) of a UUV is not known, the relationship from

Figure B3 could be confidently used to provide a value to use in propulsive calculations.

B.2.6 HOTEL ENERGY

It was assumed the load is constant and needs to power the UUV for the total time it is disconnected from its energy source. The time needed to support the hotel load is thus twice the transit time plus the time on-station. It was assumed that during recharging, no energy is expended by the UUV's batteries. By extension, it was assumed the energy storage required for the hotel loads is linearly proportional to the total time away from the SSH(N). Thus, hotel energy has been modelled by:

$$\text{Hotel Energy}=P_{Hotel}\left(2\frac{TD}{TS}+ET\right)=P_{Hotel}\left(2\frac{TD}{\alpha\, TS_{opt}}+ET\right) \qquad \text{[Eqn. B9]}$$

B.2.7 TOTAL ENERGY

Combining the hotel and propulsion energy models in Eqn. B5 gave:

$$E_{Total}= P_{Hotel}\left(2\frac{TD}{\alpha\, TS_{opt}}+ET\right)+0.5\rho A C_D \eta^{-1}\left(\alpha\, TS_{opt}\, SRe\right)^3\left(2\frac{TD}{\alpha\, TS_{opt}}\right) \qquad \text{[Eqn. B10]}$$

Usefully this has been rearranged to give an equation for the transit distance (TD)

$$TD=\frac{\alpha\ TS_{opt}(E_{Total}-P_{Hotel}ET)}{2\left(P_{Hotel}+0.5\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)} \quad \text{[Eqn. B11]}$$

TD was differentiated with respect to α (noting that P_{Hotel} is not a function of α):

$$\frac{dTD}{d\alpha}=\frac{TS_{opt}(E_{Total}-P_{Hotel}ET)\ \left(P_{Hotel}+\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)}{\left(P_{Hotel}+0.5\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)} \quad \text{[Eqn. B12]}$$

For all non-trivial and physically possible solutions when finding the maximum value for TD:

$$\frac{dTD}{d\alpha}=0=\frac{TS_{opt}(E_{Total}-P_{Hotel}ET)\ \left(P_{Hotel}-\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)}{\left(P_{Hotel}+0.5\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)} \quad \text{[Eqn. B13]}$$

Thus, this simplified to:

$$\frac{dTD}{d\alpha}=0=\left(P_{Hotel}-\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right) \quad \text{[Eqn. B14]}$$

Rearranged to find the hotel power:

$$P_{Hotel}=\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}=\rho AC_{D}\eta^{-1}\left(TS_{opt}\ SRe\right)^{3} \quad \text{[Eqn. B15]}$$

The implication of Eqn. B13 and Eqn. B15 is that regardless of the time on station (ET), the most efficient power distribution between the hotel and propulsive power (to achieve the maximum TD i.e. α=one and ET=0 hours) is for hotel power to be double the propulsive power during transit at the optimum velocity to maximise range. This suggests low UUV velocities (~3 knots) for maximum range. The usefulness of using the variable α to represent transit velocity is noted, as it readily scaled the total power according to velocity.

Reinserting Eqn. B15 into Eqn. B11, the TD for a given ET was expressed by:

$$TD=\frac{\alpha\ TS_{opt}\left(E_{Total}-\rho AC_{D}\eta^{-1}\left(TS_{opt}\ SRe\right)^{3}\ ET\right)}{2\left(\rho AC_{D}\eta^{-1}\left(TS_{opt}\ SRe\right)^{3}+0.5\rho AC_{D}\eta^{-1}\left(\alpha\ TS_{opt}\ SRe\right)^{3}\right)}=$$

$$\frac{\alpha\ TS_{opt}\left(E_{Total}-\rho AC_{D}\eta^{-1}\left(\ TS_{opt}\ SRe\right)^{3}\ ET\right)}{2\left(\rho AC_{D}\eta^{-1}\left(TS_{opt}\ SRe\right)^{3}(1+0.5\alpha^{3})\right)}=\left(\frac{\alpha\ TS_{opt}}{2(1+0.5\alpha^{3})}\right)\left(\frac{E_{Total}}{\rho AC_{D}\eta^{-1}\left(TS_{opt}\ SRe\right)^{3}}-ET\right) \quad \text{[Eqn. B16]}$$

Finally, after substituting in Eqn. B4:

$$TD=\left(\frac{\alpha\ TS_{opt}}{2(1+0.5\alpha^{3})}\right)\left(\frac{c_{3}\ VD}{\rho A\eta^{-1}\left(TS_{opt}\ SRe\right)^{3}}-ET\right) \quad \text{[Eqn. B17]}$$

UUV manufacturers will often give a value for TS_{opt} however if the value not specified, an approximately can be found by manipulating Eqn. B17. Preference in the Payload Calculator program was given to the manufacturer's value, as it is likely that this has been found by real world tests, and thus more accurate.

FRACTION OF TOTAL UUV NUMBER ON STATION:
Total time for the round trip of a single UUV is:

$$\text{Total Trip Time}=2\frac{TD}{TS}+ET+MT=2\frac{TD}{\alpha TS_{opt}}+ET+MT \qquad \text{[Eqn. B18]}$$

The fraction of total time on station is:

$$\text{Fraction of total time on station}=\frac{ET}{2\frac{TD}{\alpha TS_{opt}}+ET+MT} \qquad \text{[Eqn. B19]}$$

Thus, the number of UUVs (allowing for the Loss Rate – LR[1]) on-station has been modelled as:

$$N_s=\frac{N_T ET}{LR\left(2\frac{TD}{\alpha TS_{opt}}+ET+MT\right)} \qquad \text{[Eqn. B20]}$$

This was rearranged to:

$$2\frac{TD}{\alpha TS_{opt}}=\frac{N_T ET}{N_s LR}-MT-ET \qquad \text{[Eqn. B21]}$$

B.2.8 FRACTION OF TOTAL UUV NUMBER CONNECTED TO AN SSH(N):

The time a UUV is connected to a recharging point, called maintenance time (MT) is:

$$\text{The fraction of total time taken up by MT }=\frac{MT}{(2\frac{TD}{\alpha TS_{opt}}+ET+MT)} \qquad \text{[Eqn. B22]}$$

The number of UUVs or connected to a Category A UUV hub for a UUV cluster or SSH(N) for a Category A UUV, has been modelled so that the maintenance time (MT) varies for each UUV. The proposed model is Eqn. B23.

$$MT=c_5(N_{UUV})^{c_4}+c_6=c_5\left(\frac{N_T MT}{LR(2\frac{TD}{\alpha TS_{opt}}+ET+MT)}\right)^{c_4}+c_6 \qquad \text{[Eqn. B23]}$$

Eqn. B23 reflects that there is a baseline rate at which a UUV is connected to a power source and that the maintenance time will exponentially ramp up as more and more UUVs are simultaneously connected, as facilities and recharging resources are stretched. It was assumed that if the model simply reflected the queuing of UUVs awaiting charging, the ramp up in MT would be purely linear. However,

[1] The Loss Rate represents the number of UUVs lost on a mission per UUV.

there are also non-linear elements that have been incorporated into the model. All the equations have the underlying assumption that all UUVs discharge all their stored energy performing their missions.

If MT is a small fraction of the total mission time, the value for MT will be constant (equal to c_6), regardless of the total number of UUVs (N_T). A value of 5.0% or less of MT (as a proportion of total mission time) was considered a good point at which to consider MT as constant. This produced a 20% error (relative to c_4) for the value of MT if the total number of UUVs was 34, which was considered acceptable for approximating MT.

Putting in the expression for TD (Eqn. B17) in Eqn. B23 gave:

$$MT(MT,ET,\alpha)=c_5\left(\frac{N_T MT}{LR\left(2\frac{\left(\frac{\alpha\ TS_{opt}}{2(1+0.5\alpha^3)}\right)\left(\frac{c_3\ VD}{\rho A\eta^{-1}\left(TS_{opt}\ SRe\right)^3}-ET\right)}{\alpha TS_{opt}}+ET+MT\right)}\right)^{c_4}+c_6 \quad \text{[Eqn. B24]}$$

This equation was used to model the effects of the ‘optimum’ MT, i.e. minimise as per the models used in the Payload Calculator.

Eqn. B23 can be rearranged to produce the relationship:

$$ET+2\frac{TD}{\alpha TS_{opt}}=\left(\frac{N_T MT(MT,ET,\alpha)}{LR}\right)\left(\frac{MT(MT,ET,\alpha)-c_4}{c_3}\right)^{-1/c_2}-MT \quad \text{[Eqn. B25]}$$

Usefully, total time for the round trip of a single UUV could be expressed as:

$$\text{Total Trip Time}=2\frac{TD}{\alpha TS_{opt}}+ET+MT(MT,ET,\alpha)$$
$$=\left(\frac{N_T MT(MT,ET,\alpha)}{LR}\right)\left(\frac{MT(MT,ET,\alpha)-c_6}{c_5}\right)^{-1/c_4} \quad \text{[Eqn. B26]}$$

This will assist in identifying values for constants by relating it to an understandable quantity

B.2.9 CHARACTERISTIC EQUATION FOR THE STEADY STATE MODELLING OF THE SYSTEM

If the rate of UUVs coming onto station must equal at all times the rate at which they go off-station and return to the SSH(N), Eqn. B20 was rearranged to give:

$$\frac{ET}{N_s}=\frac{MT(MT,ET,\alpha)+2\frac{TD}{\alpha TS_{opt}}}{\frac{N_T}{LR}-N_s} \qquad \text{[Eqn. B27]}$$

B.2.10 FRACTION OF UUVS ON STATION (FINAL EQUATION)

Thus, using Eqn. B27, Eqn. B25 and B24 the number of UUVs (N_s) on station could be modelled as:

$$N_s=ET\left(\frac{\frac{N_T}{LR}-N_s}{MT(MT,ET,\alpha)+2\frac{TD}{\alpha TS_{opt}}}\right)=\frac{N_T}{LR}\left(\frac{ET}{MT(MT,ET,\alpha)+2\frac{TD}{\alpha TS_{opt}}+ET}\right)=$$

$$\frac{N_T}{LR}\left(\frac{ET}{MT(MT,ET,\alpha)+2\frac{\left(\frac{\alpha\, TS_{opt}}{2(1+0.5\alpha^3)}\right)\left(\frac{c_3\, VD}{\rho A\eta^{-1}\left(TS_{opt}\, SRe\right)^3}-ET\right)}{\alpha TS_{opt}}+ET}\right)= \qquad \text{[Eqn. B28]}$$

$$\frac{N_T}{LR}\left(\frac{ET}{MT(MT,ET,\alpha)+\left(\frac{1}{(1+0.5\alpha^3)}\right)\left(\frac{c_3\, VD}{\rho A\eta^{-1}\left(TS_{opt}\, SRe\right)^3}-ET\right)+ET}\right)$$

The constants were either found through trial and error or where applicable were already fixed.

c_1=3297600[J]; c_2=3.0; c_3=5×3600=18000[s]; c_4=5×3600=18000[s]; LP=1.1;

C_1 Is the constant of proportionality between UUV displacement and ratio of stored energy to the coefficient of drag in S.I. units, found from Figure B1.

C_2 = 5 hours as to imply that the increase in maintenance time (MT) for small additional numbers of UUVs on board the SSH(N) is minimal.

C_3 is set to provide a baseline MT of 5 hours. This was assumed a typical charging time.

C_4 is set as 1.1 – thus a loss percentage (LP) of 10%. This was assumed an acceptable percentage loss rate of UUVs on a mission.

B.3 ANALOGY OF AN ENERGY MINIMISATION TECHNIQUE FOR CONSTRUCTION OF USGOT

B.3.1 INTRODUCTION

This section details the finite element analysis (FEA) energy minimisation technique based on theory put forward by Zienkiewicz et al. (2005), used to 'optimise' the UUV net (as defined by maximising a USGOT-specific metric called the 'equivalent area').

B.3.2 CONNECTED UUVS

Due to a lack of data for sensor ranges, it was assumed the probability of detecting a target by a vehicle simply decreased linearly with distance from the target, as shown in Figure B4. At the limit of the UUV (node) sensor range (SR_n), the probability of detection would be zero.

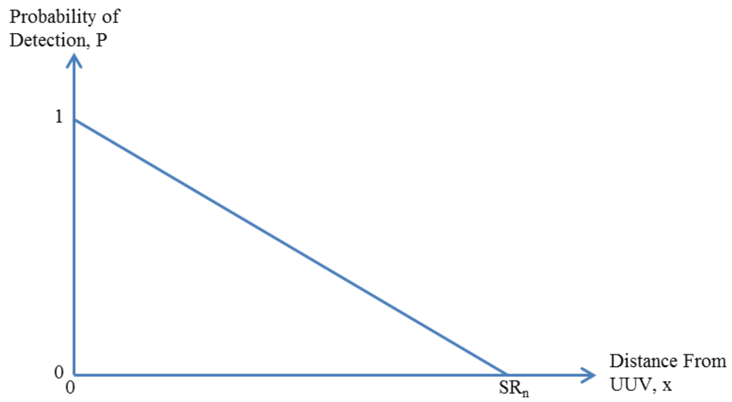

Figure B4 – Model Employed of Distance of UUV vs. Probability of Target Detection

The connection between two UUVs could be considered analogous to two nodes connected elastically in an FEA model. The connection between two UUVs would be considered valid if the union probability of detecting a target crossing a connecting line between the two UUVs was above the probability limit specified in a USGOT simulation. This criterion applied for all locations along a connecting line. This is illustrated in Figure B5. A value for this limit for the safe minimum probability of detection of a target was assumed at 95% in all USGOT simulations in the current research.

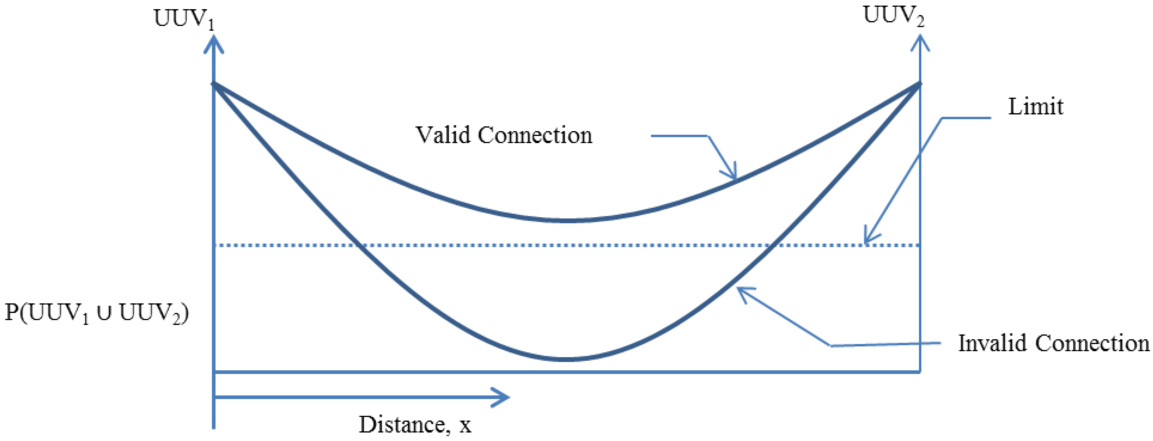

Figure B5 – Identifying a Valid Connection between Two Nodes

B.3.3 UUV GRID OPTIMISATION

9.3.3.i Two-Node Connections

An energy minimisation technique analogous to FEA (Zienkiewicz, et al., 2005) was adopted to find the positions of the UUVs in a grid, which maximised a metric devised by the candidate the 'equivalent area' (it is defined in Chapter 3). The UUVs in a grid were modelled as nodes; the probability of detection of a target by a UUV was taken as akin to FEA stiffness in elements and forces applied in such a way that the UUV net pre-solution could be considered to be 'in compression'. The probability of target detection by a UUV in the grid is calculated by Eqn. B29:

$$P(P_1 \cup P_2)=1-Q_1Q_2=1-\left(\frac{x-x_1}{SR_{n1}}\right)\left(\frac{x_2-x}{SR_{n2}}\right)=1-\frac{-x^2-x_1x_2+x(x_2+x_1)}{SR_{n1}SR_{n2}} \qquad \text{[Eqn. B29]}$$

The probability of target detection between a pair of UUVs was found from Figure B6

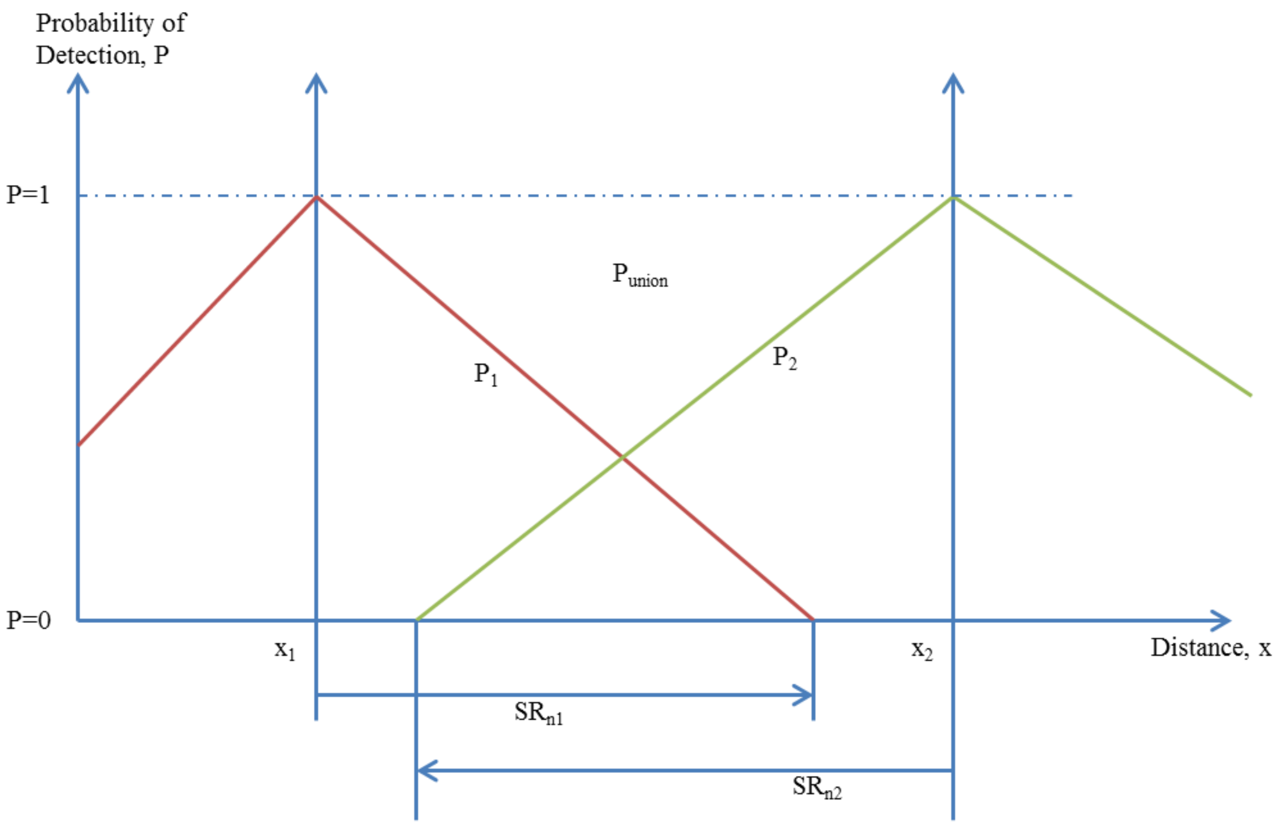

Figure B6 – The Union Probability of Target Detection between any Two UUVs

This produces a probabilistic minimum shown in Figure B6 and given by:

$$P(P_1 \cup P_2)_{min} = \frac{(x_2 - x_1)^2}{4SR_{n1}SR_{n2}} \qquad \text{[Eqn. B30]}$$

The force (F), which is always attempting to expand the grid and, thus, the distance between the two nodes to the maximum possible amount, is proportional to the difference between the probabilistic minimum and the Limit. The (theoretical) force will only "exist" if there is a probabilistic connection between the two nodes. The force is found by:

$$F = (1-L) - \frac{(x_2 - x_1)^2}{4SR_{n1}SR_{n2}} \qquad \text{[Eqn. B31]}$$

Rearranging and collecting the 'Force', 'Stiffness' and Displacement terms:

$$\text{'Force'} : 1-L-F \qquad \text{[Eqn. B32]}$$

$$\text{'Stiffness'}(k) : (4SR_{n1}SR_{n2})^{-1} \qquad \text{[Eqn. B33]}$$

$$\text{Displacement} : (x_2 - x_1)^2 \qquad \text{[Eqn. B34]}$$

To simplify:

$$F' = 1 - L - F \qquad \text{[Eqn. B35]}$$

The governing equation is thus:

$$F'(x) = ku \qquad \text{[Eqn. B36]}$$

The 'applied force' components are:

$$F'_x = F' \frac{(x_2 - x_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad \text{[Eqn. B37]}$$

$$F'_y = F' \frac{(y_2 - y_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad \text{[Eqn. B38]}$$

The 'displacement' components are:

$$u_x = (x_2 - x_1)^2 \qquad \text{[Eqn. B39]}$$

$$u_y = (y_2 - y_1)^2 \qquad \text{[Eqn. B40]}$$

9.3.3.ii Multiple-Node Connections

A polygon set of UUVs has been defined as a number of nodes that can project influence on one another, i.e. are within range with each other and are probabilistically connected to at least one other node in the polygon set (to ensure there are no 'orphan' nodes). Thus, if the locations of the nodes and connection lines are plotted, they form a polygon. An illustration of a polygon set is shown in Figure B7.

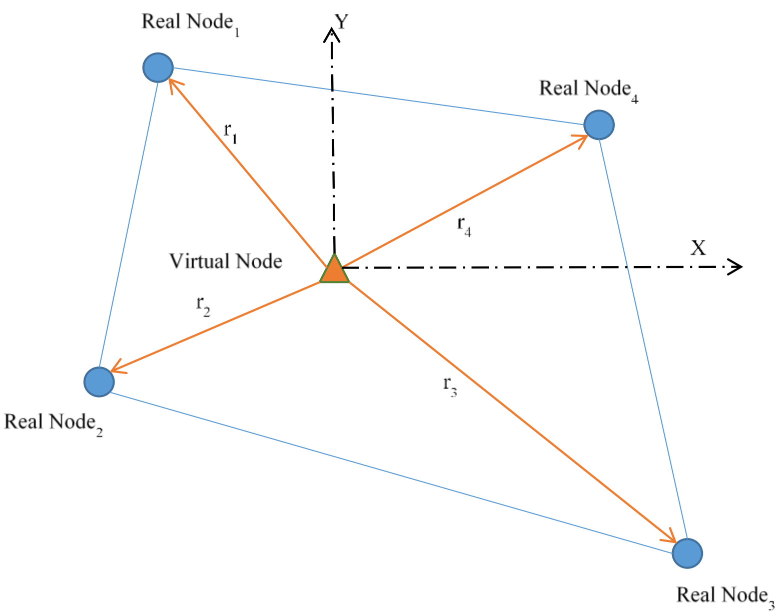

Figure B7 – A Typical Polygon Set Created by the UUV (Real) Nodes

The mathematics describing the interactions in Figure B7 between more than two nodes in a set is significantly more complex, with no analytical solution readily available. The solution developed by the candidate is the use of imaginary 'virtual nodes' (VN) to model the combined probabilistic influence other real nodes (i.e. UUVs) have on each real node within a polygon set. The consideration of polygon sets of UUVs of more than two UUVs was considered necessary to provide a sufficiently high degree of realism to the operational analysis by facilitating the generation of improved UUV nets by USGOT. A virtual node's sensor range (SR_n) is calculated from conjoining probabilistic effects of the other nodes with respect to a selected real node (denoted by the subscript "1"). Its SR_n value is such that it is equivalent to an isolated two-node connection (i.e. the connection described in Figure B5) between a selected real node and the virtual node. The virtual node's location is always defined to produce the lowest combined detection probability of all the nodes in the polygon to ensure every point on the connection lines is above the limit – i.e. valid.

From the model described in Figure B5 for how probability of detection varies with range from a specific UUV (denoted by 'i'):

$$P_{ReN_i}(r_i)=1-\frac{r_i}{SR_{n_i}} \qquad \text{[Eqn. B41]}$$

Recalling that P can also be expressed by:

$$P_{RN_i}=1-Q_{ReN_i} \qquad \text{[Eqn. B42]}$$

Thus, if 'r' represents the radial distance from a node, the probability of non-detection can be described by:

$$Q_{ReN}(r_i)=\frac{r_i}{SR_{n_i}} \qquad \text{[Eqn. B43]}$$

As it is the union probability that produces the probability of detection between multiple nodes, it was concluded that it was mathematically simpler to calculate the *probability of non-detection*. Thus, to calculate the non-detection probability of a VN:

$$Q_{VN}=\prod_{i=1}^{n} Q_{ReN_i}(r_i) \qquad \text{[Eqn. B44]}$$

Thus, the *equivalent* probability of detection (P_{eq}) along the connecting line from the virtual node (VN) to a selected real node (ReN_1) becomes:

$$P_{eq}(r)=1-Q_{VN}(r)Q_{ReN_1}(r) \qquad \text{[Eqn. B45]}$$

Thus, this can alternatively be expressed as:

$$1\text{-}P_{eq}(r)=Q_{eq}(r)=Q_{VN}(r)Q_{ReN_1}(r) \qquad \text{[Eqn. B46]}$$

The local coordinates system was selected with the origin at the global coordinates for the virtual node, again to simplify the equations. However, as a result, when polygon nodes are displaced due to solving the 'FEA' problem, the VN will no longer have the same value for the probability of detection (or probability of non-detection). This is because its location relative to the real nodes associated with the polygon will have also changed. Furthermore, it proved impractical to calculate the position of a VN relative to the real nodes as an increasing number of nodes forming a polygon exponentially increases the amount of required computation.

Thus, to overcome this impracticality, a representative virtual node (VN_1) can be defined, which is initially located very close (effectively co-indecent) to the specified real node. The scalar field, λ_1, was defined to represent the combined effects of the VN on the specific real node (ReN_1). It does this by expressing the value for Q_{VN1} for a location somewhere in the polygon set (using local co-ordinates) as an equivalent value of Q_{RN1} at the location of the 'true' VN. This allows a value for λ_1 at a known position to be calculated.

By locating the representative virtual node so close to the selected real node (RN_1) in the first instance, the effect of the direction of VN_1 relative to RN_1 should always be nullified. This allows the 'true' VN, VN_1 and RN_1 to be modelled as always aligned with a single vector. The position and related value of the 'true' VN cannot readily be solved analytically; however, its effects on each of the real nodes can be modelled, using the scalar field λ_1.

If the radial distance of VN_1 to ReN_1, is said to be effectively zero, and so gives:

$$Q_{VN_1}(0)Q_{ReN_1}(r_1)=Q_{eq_1}(0)=Q_{ReN_1}(r_1)\prod_{i=2}^{n} Q_{ReN_i}(r_i) \qquad \text{[Eqn. B47]}$$

It was considered that if the value for the probability of non-detection for the 'true' VN (Q_{VN}) was known before the 'FEA' is solved, the value of the scalar λ_1, corresponding to a specific ReN, could be initially calculated. Thus, the influence of ReN_1 at the location of the 'true' VN (before the FEA is solved) could be scaled for its influence on a representative virtual node, VN_1:

$$Q_{VN_1}(0)=\left[\lambda_1(x,y)\ Q_{ReN_1}(r_1)\right] \qquad \text{[Eqn. B48]}$$

Inserting Eqn. B48 into Eqn. B47:

$$Q_{eq_1}(0)=Q_{VN_1}(0)Q_{ReN_1}(r_1)=\left[\lambda_1(x,y)\ Q_{ReN_1}(r_1)\right]Q_{ReN_1}(r_1) \qquad \text{[Eqn. B49]}$$

This in turn gave:

$$\lambda_1(x,y)Q_{ReN_1}(r_1)=\prod_{i=2}^{n} Q_{ReN_i}(r_i) \qquad \text{[Eqn. B50]}$$

Thus, recalling Eqns. B43 and B44 gave:

$$\lambda_1(x,y)=\frac{\prod_{i=2}^{n} Q_{ReN_i}(r_i)}{Q_{ReN_1}(r_1)}=\left(\frac{\prod_{i=2}^{n} r_i}{\prod_{i=2}^{n} SR_{n_i}}\right)\left(\frac{SR_{n_1}}{r_1}\right) \qquad \text{[Eqn. B51]}$$

If λ_1 is graphed as a function, there is one pole at the selected real node (ReN_1) and zeros at the location of every other real node location. If the zeros are combined into single, far off zero (relative to a very short distance to a zero node location), the following model could approximate the value of λ_1, using a vector α to represent the line between the zeros and pole:

$$\lambda(\alpha)=\frac{\alpha_0-\alpha}{\alpha}=\frac{\alpha_0}{\alpha}-1 \qquad \text{[Eqn. B52]}$$

This equation is illustrated in Figure B8:

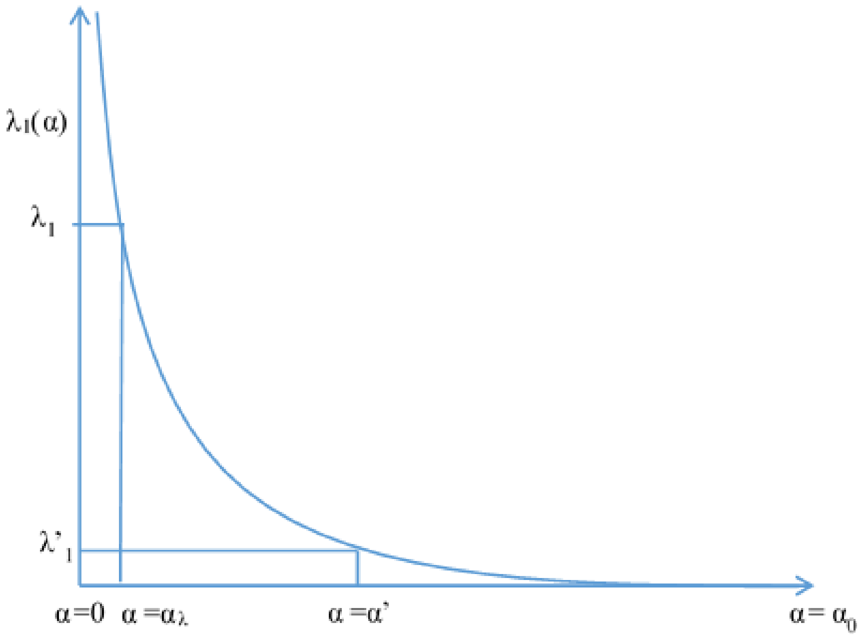

Figure B8 – Modelling the Value for λ_1 along the α-Axis.

The zero is at the location α_0 (in the computer program this is taken as the real node furthest away from the selected node – to provide reliability). The mathematical model in Figure B8 is illustrated in Figure B9:

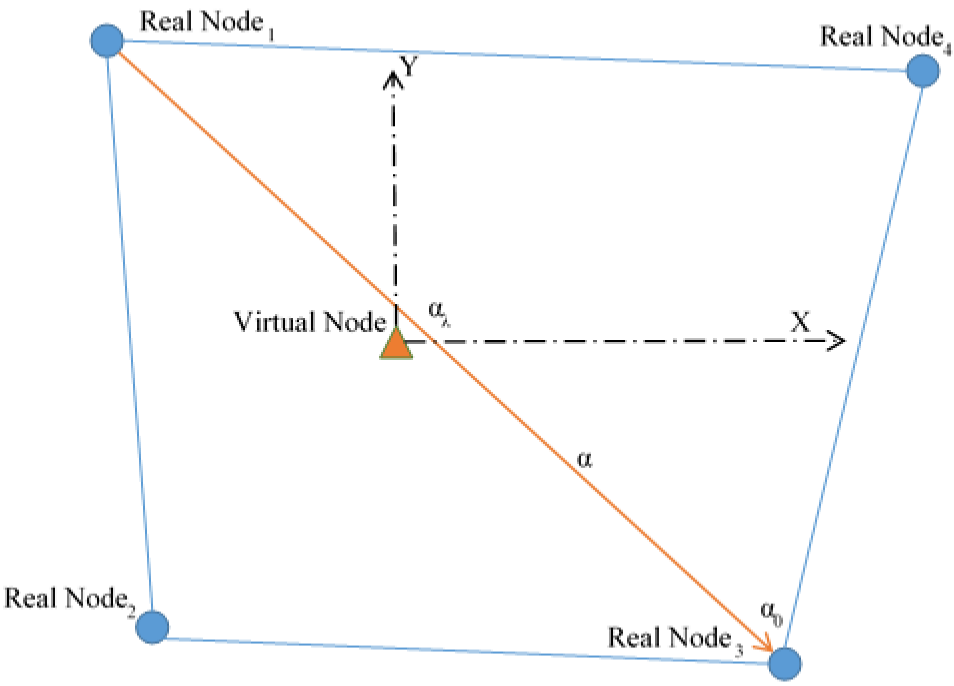

Figure B9 – Approximately Locating the VN on the α Axis

Thus, for a representative VN's scaling (using Eqn. B51):

$$\lambda_1(\alpha)=\frac{\prod_{i=2}^{n} Q_{ReN_i}(r_i)}{Q_{ReN_1}(r_1)}=\left(\frac{\prod_{i=2}^{n} r_i}{\prod_{i=2}^{n} SR_{n_i}}\right)\left(\frac{SR_{n_1}}{r_1}\right) \qquad \text{[Eqn. B53]}$$

A position (α') that is very close to α_0 is selected from which λ_1 is said to be always small, regardless of small variations in the value for λ_1 (1% of the total length of α was found by trial and error to work well). This was to both minimise the effect of approximating all the poles to a single point, <u>and</u> the effect of shifting the specific real node's location during the solving of the 'FEA' problem.

Thus, according to Eqn. B53, a representative VN far away from the selected real node has a corresponding higher SR_n. If a representative VN has location that is far away – allowing the grouping of all the zeros – the effect of small shifts in the direction of the VN becomes negligible, in terms of the influence the VN has on the selected real node. This allowed the effects on the VN to be modelled during the solving of the 'FEA' problem.

At α' an approximated value for lambda can be found. With this position and value of lambda known, the equivalent value for the 'true' VN expressed as a fraction of ReN_1 can also be found. At $\alpha = \alpha_0$, $r = r'_1$ and r'_3 is very small at 1% of the total length of α (with ReN_3 being the furthest real node from ReN_1 in the example shown in Figure B10).

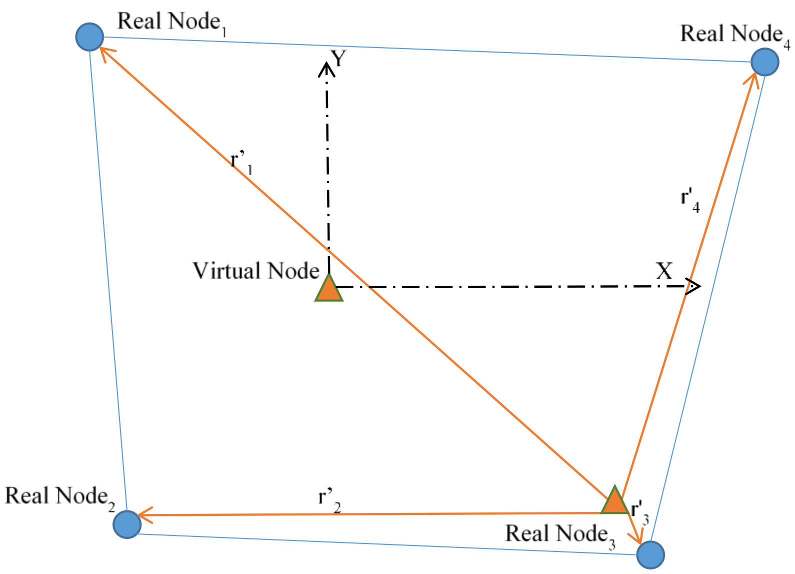

Figure B10 – Imagining the Representative VN a Long Distance (r'_1) from RN_1

As everything scales, the influence of the specific real node at the 'true' virtual node can be expressed using Eqn. B53:

$$\frac{\lambda_1(\alpha)Q_{ReN_1}(r_1)}{\prod_{i=2}^{n} Q_{ReN_i}(r_i)} = \frac{\lambda_1(\alpha')Q_{ReN_1}(r'_1)}{\prod_{i=2}^{n} Q_{ReN_i}(r'_i)} \qquad \text{[Eqn. B54]}$$

The virtual node was modelled as a node with an equivalent sensor range (SR_n). This is because each representative VN that corresponds to a selected real node will be placed on the UUV net.

To find the sensor range of VN_1 at $\alpha = \alpha'$ using Eqn. B53:

$$Q_{ReN_1}(r'_1) = \frac{\prod_{i=2}^{n} Q_{ReN_i}(r'_i)}{\lambda_1(\alpha')} = \frac{r'_1}{SR_{n1}} \qquad \text{[Eqn. B55]}$$

Thus, recalling Eqn. B55:

$$\lambda_1(\alpha')Q_{ReN_1}(r'_1) = \lambda_1(\alpha')\frac{r'_1}{SR_{n1}} = \frac{r'_1}{SR'_{n1}} \qquad \text{[Eqn. B56]}$$

Hence using Eqn. B56:

$$SR'_{n1} = \frac{SR_{n1}}{\lambda_1(\alpha')}$$ [Eqn. B57]

This equation could then be used to represent the effects of a virtual node to a specific real node within the polygon set, with each real node interacting with a single corresponding representative virtual node approximately modelling the effects of the 'true' virtual node. This approximation should remain valid, if the changes in the 'true' VN's relative location remain relatively small.

B.4 IMPLEMTATION OF USGOT IN MATLAB

B.4.1 DESCRIPTION

A function in MATLAB called the Payload Calculator was created to calculate the 'optimum' trade-off between MT, ET, TS and NT using Eqn. B28. The single variable to be 'optimised' using Eqn. B28 has been called the score, φ, which is the product of TD and N_s. φ must be minimised (not maximised) in MATLAB due to the optimisation function algorithms always being coded to minimise a function (as per convention).

The partial differentials at the 'optimum' solution could also be calculated. These could be used to understand the sensitivities of each variable and thus, in turn suggest improvements and likely trends in the future characteristics of UUVs.

The minimisation MATLAB function "fmincon" was chosen to search for this 'optimum' trade-off. It was selected as it could handle multiple input variables to minimise a single output variable as well as being able to address both linear and nonlinear inequalities (when using the "confun" function, which allows for inequality constraints).

B.4.2 STARTING POINT VECTOR

The minimisation function needs a starting value for each input variable (in the vector X_0 that contains the starting value for each variable). A sensible set of values should be selected (i.e. considered likely to be close to the 'optimised' solution) as this reduces the computation and hence solution time. Even more importantly, it reduces the chance of the function converging on a local and not the global minima solution for φ. It is noted that the MATLAB code has written into it an iterative loop that is intended to ensure the starting values supplied could provide an optimised solution that is valid (i.e. satisfying all the inequalities making the solution valid and ergo practical). Typical starting values are:

MT=5 [hours]   ET=20 [hours] α=0.5   [@TS_{opt} = 4 knots]

B.4.3 INEQUALITY CONSTRAINTS

9.3.3.iii Description

Inequality constraints were placed on the search for a solution for minimising φ. These ensured that the solution generated by the MATLAB program using the Payload Calculator during the USGOT simulations in this thesis were always practical. Both linear and non-linear constraints were used.

9.3.3.iv Linear Constraints

These constraints were different for each UUV. For the Hugin 1000 UUV, these were taken as:

$$0.5 \leq \propto \leq 1.5;\ 10\ \text{hours} \leq ET \leq 24\ \text{hours};\ 5\ \text{hours} \leq MT \leq 15\ \text{hours}$$

9.3.3.v Nonlinear Constraints

$$\lfloor N_s \rfloor \leq \frac{N_T}{1.25};\ \lfloor N_s \rfloor \geq \frac{N_T}{5};\ TD \leq 200\ [nm];\ 20\ [nm] \leq TD$$

APPENDIX C - USGOT SCENARIO SIMULATION RESULTS

C.1 SCENARIO 1: SEA DENIAL IN LITTORAL AREAS

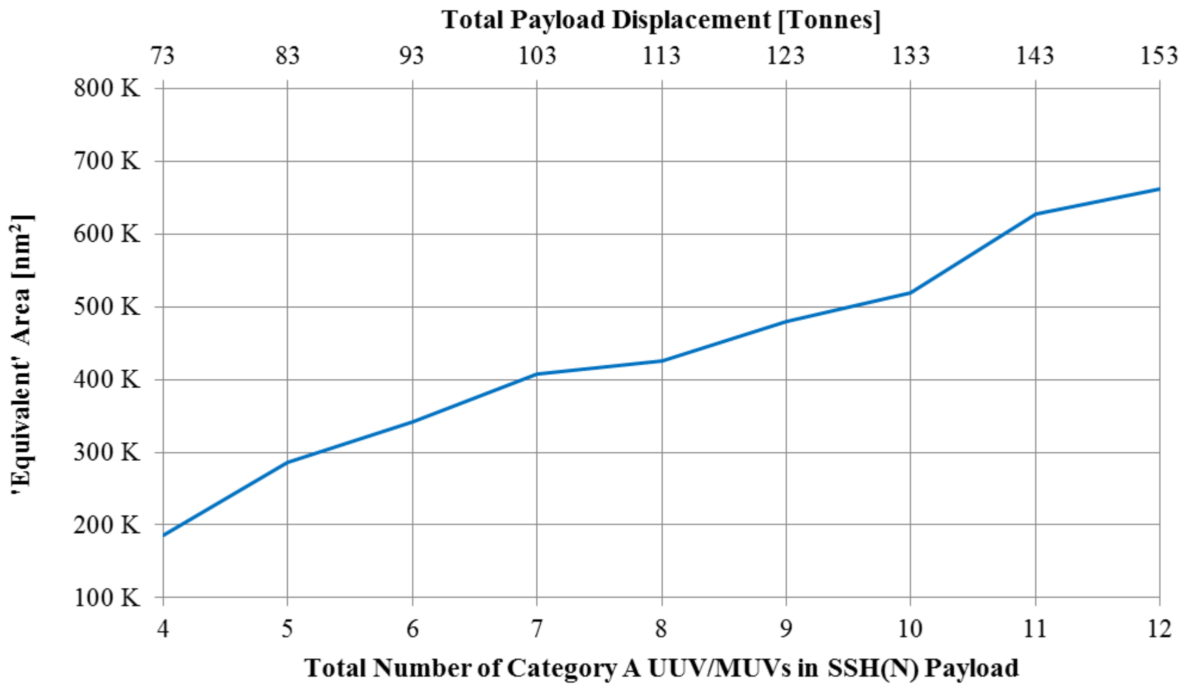

Figure C1 – Scenario 1: USGOT Results (30 Category B and 30 Category C UUVs)

There was a strong linear relationship between the 'equivalent area' metric versus the number of Category A UUVs for Scenario 1. This trend indicated the dominance of Category A UUVs, which drove the positioning of the clusters and thus primarily affected the area of the grid. If an SSH(N) only has a very small number of Category A UUV/MUVs, USGOT predicts that the radius of operation (ROO) would be limited in order to field on-station a UUV cluster. This could endanger the SSH(N) by forcing it further down threat as well as violating the scenario constraints placed on the USGOT scenario (this why four was considered to be the minimum number of Category A UUVs that should be simulated by USGOT). Furthermore, a reduced ROO could increase the risk of the SSH(N) being detected by enemy vessels, thus disrupting the mission.

C.2 SCENARIO 2: TACTICAL STRIKE AGAINST ENEMY COASTAL DEFENCE

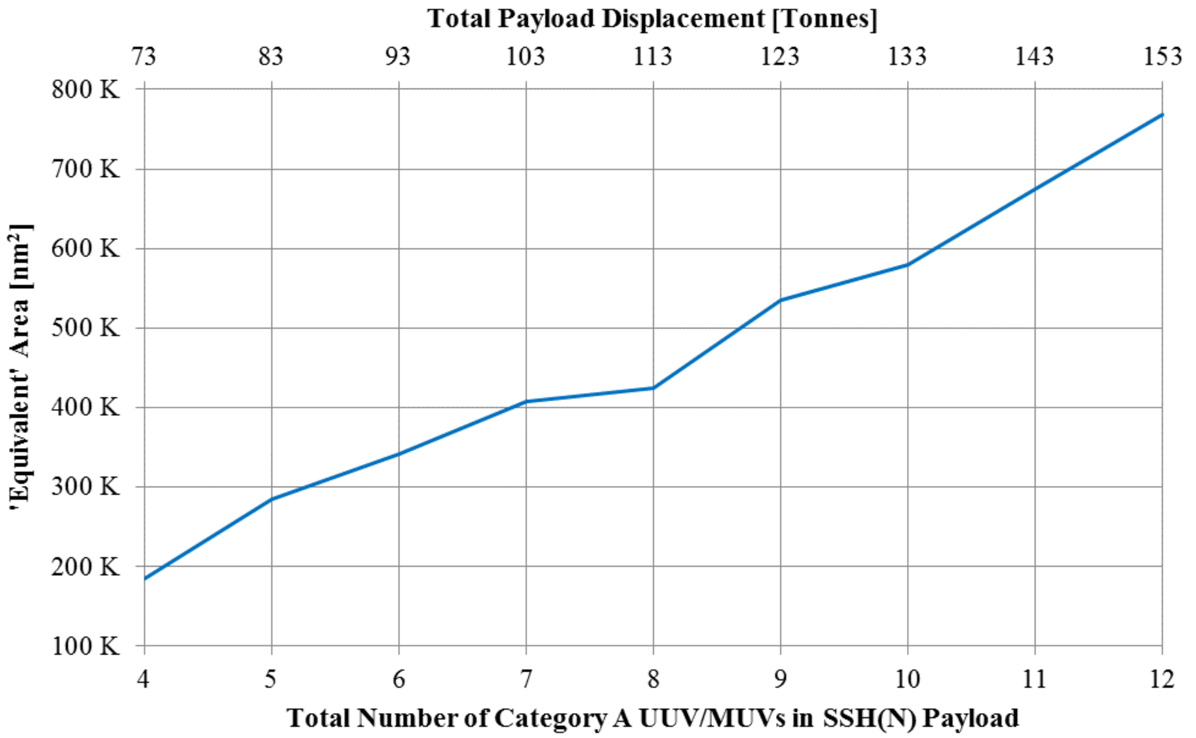

Figure C2 – Scenario 2: USGOT Results (30 Category B and 30 Category C UUVs)

As with Scenario 1, Figure C2 shows a strong linear relationship between Category A UUV/MUVs and the 'equivalent area'. Again, the minor perturbations from pure linearity in Figure C2 indicates that there are preferable numbers of Category A UUVs/MUVs for the payload volume. The 'equivalent area' values are the same as in Scenario 1 for lower numbers of Category A UUVs (8 or less). This was because the distance restrictions between Category B and C UUVs in a cluster applied in Scenario 1 only took effect for the higher numbers of on-station clusters, which could be spread over a greater coverage area – increasing the distances between clusters and isolating them.

If the SSH(N) only has a very small number of Category A UUVs (e.g. 4), USGOT predicts the ROO would be limited in the same way as with Scenario 1. As with Scenario 1, this violates the operational constraint of fielding, at least, one cluster on-station permanently and thus it was impossible in USGOT to simulate less than four Category A UUVs. The effect of this would be to endanger the SSH(N) by forcing it closer to the threat to undertake a tactical strike.

C.3 SCENARIO 3: CAPITAL ASSET PROTECTION

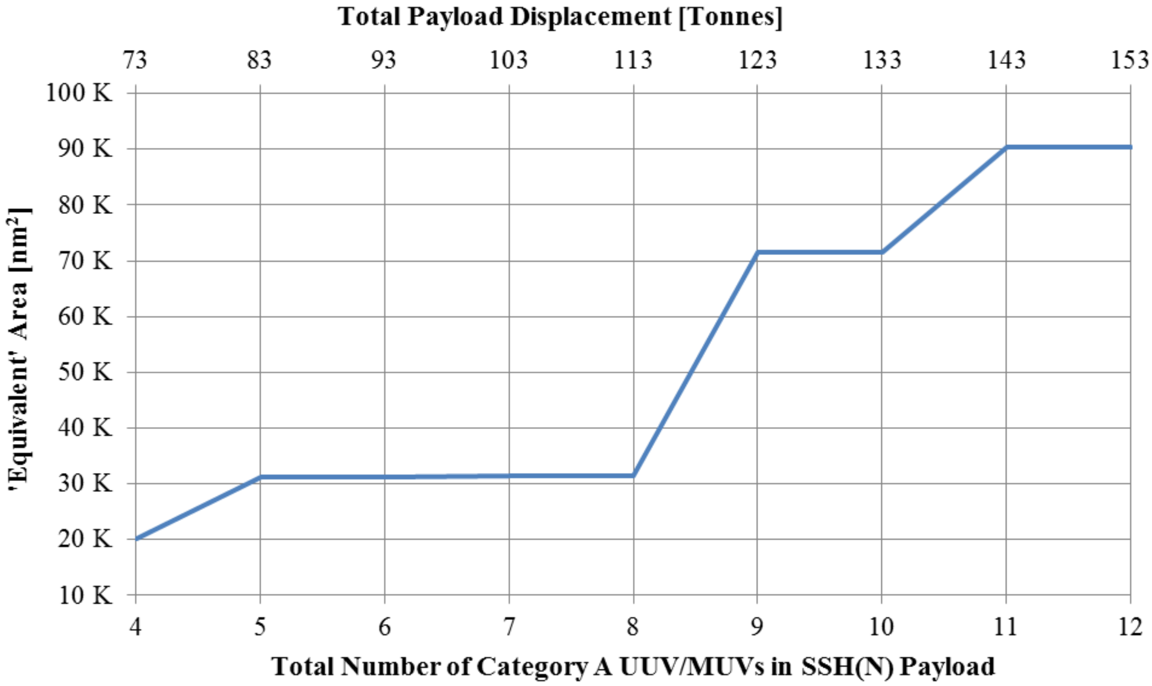

Figure C3 – Scenario 3: USGOT Results (30 Category B and 30 Category C UUVs)

For this scenario, the non-linearity in the results is far more pronounced than for Scenario 1 and 2, indicating greater impact on the UUV net capability. This arose from the operational constraint that is unique to Scenario 3. It restricted, to a greater extent than the other scenarios, the maximum distance the UUV cluster could be from the SSH(N)s. Unlike the other two scenarios, the clusters are all pulled in together to provide the maximum protection, as shown in Figure C4. In the other scenarios, the clusters would be located around 70 nautical miles from the SSH (N). There are connections between Category B and C UUVs from different clusters in Figure C4. However, since it was assumed a Category A UUV/MUV still needs to be on station to provide a localised power supply and command and control, the effect of a missing UUV/MUV (hence cluster) was simulated by USGOT as very pronounced, as demonstrated in Figure C3 by the change 'equivalent area' values for eight and nine Category A UUV/MUVs.

Current existing SSH(N)s can only accommodate a very small number of UUVs e.g. the Swedish A26 (Saab, 2015). USGOT predicts this might make it very difficult to create an effective UUV net, which is capable of encompassing and protecting a capital asset. USGOT suggests that the capital asset and potentially the SSH(N) could thus be at greater risk as there are too few UUVs on-station to provide the required defence. Based on the USGOT results, it is suggested that at least three Category A's on-station (out of four in total carried) are required to form an effective UUV net for the capital asset protection scenario.

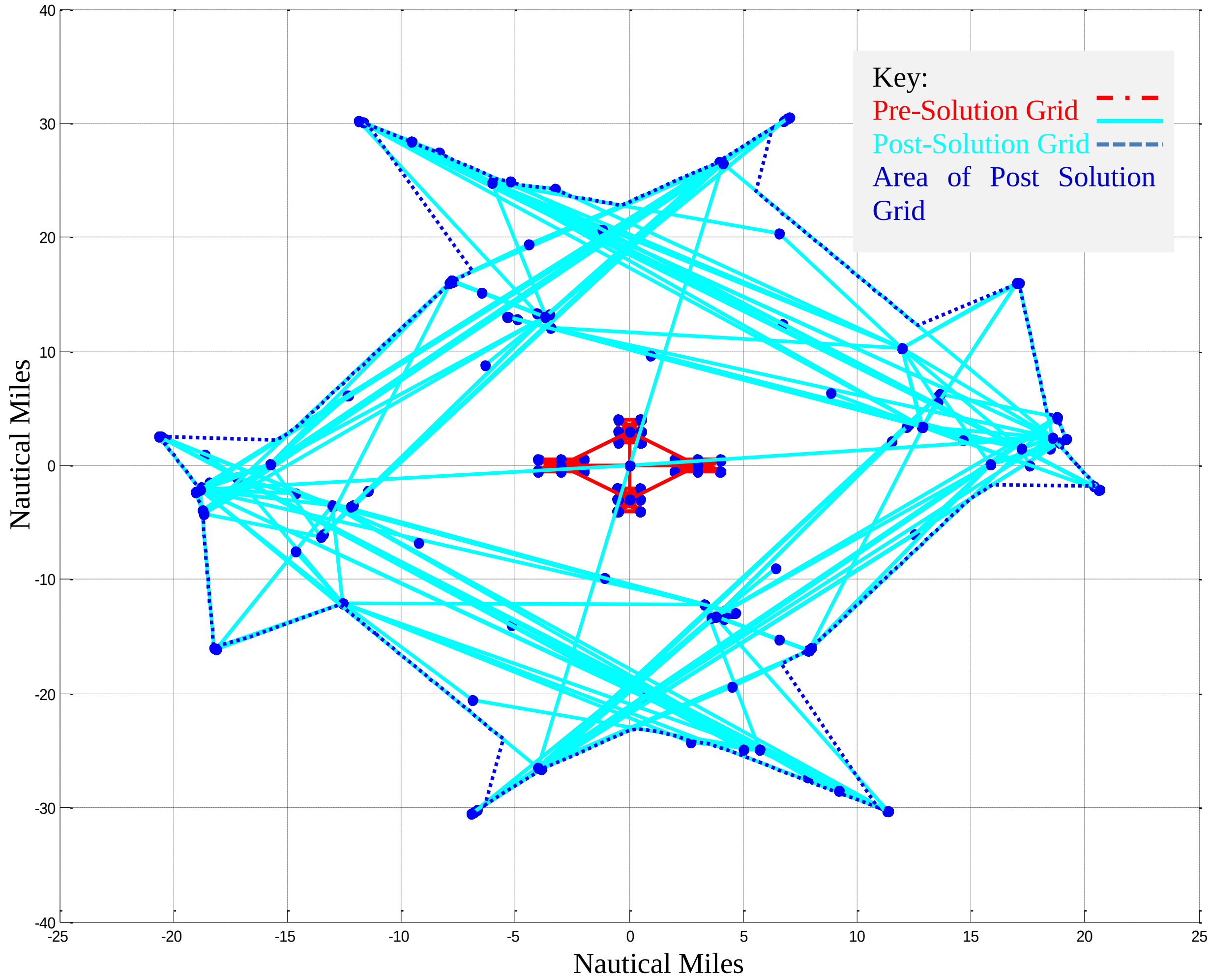

Figure C4 – Scenario 3 Simulation (7 Category A, 30 Category B and C UUVs)

APPENDIX D - SUPPORTING NOTES FOR SUPERB

D.1 BURCHER AND RYDILL'S SUBMARINE SIZING PROCEDURE

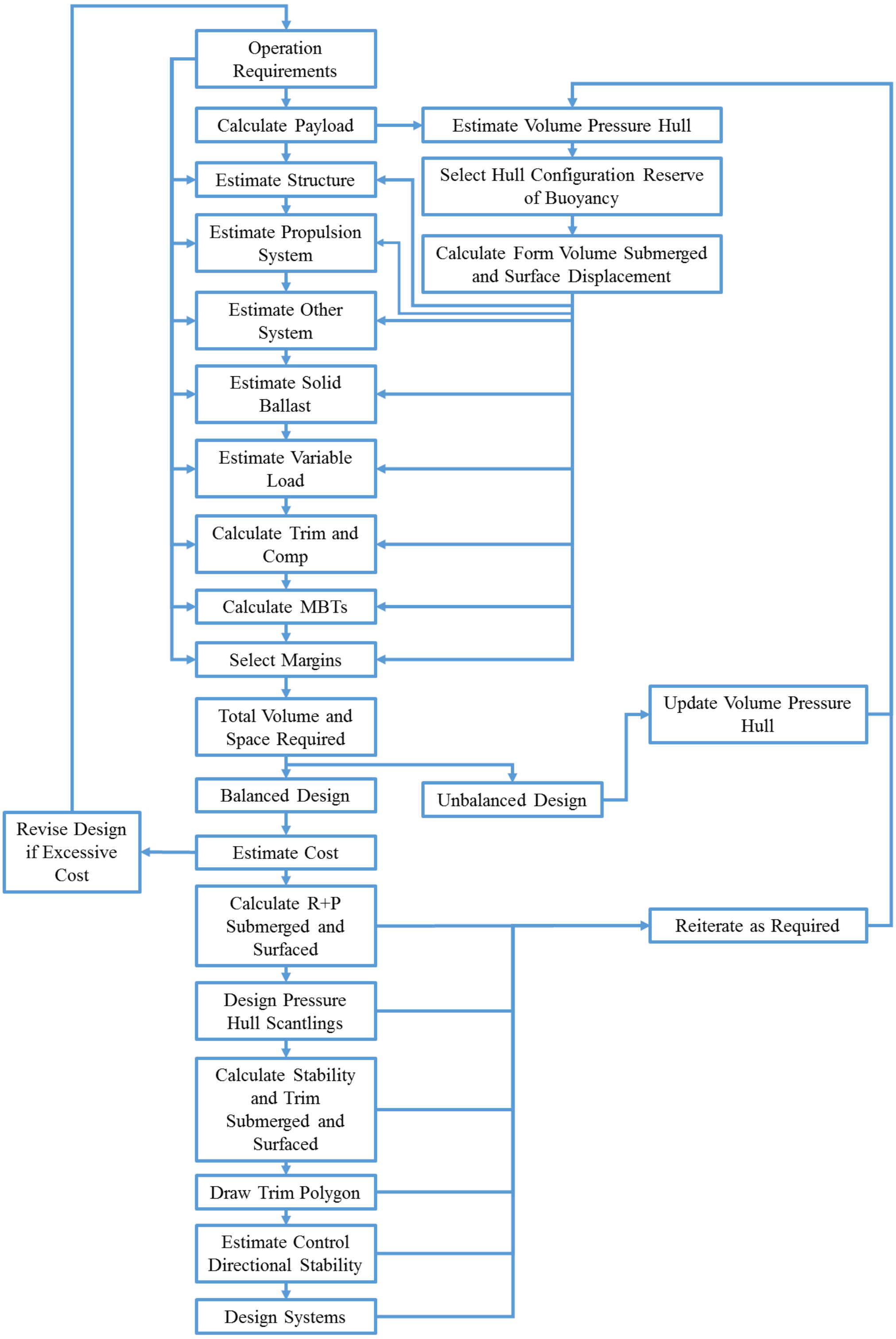

Figure D1 – "Submarine Sizing Procedure", Figure 11.4, pp 265-7 of Burcher & Rydill (1994)

D.2 TOP LEVEL DESIGN INPUT VARIABLES FOR SUPERB

Table D1 – Typical Set of Top Level Input Variables Used in SUPERB

System	Input Variable	Units	Range of Value (Increment)
Strength	Submerged Displacement	te	3,000-15,000 (2,000)
	RoB	%	5-25 (5)
	DDD	m	200-1000 (100)
	Hover Ability	n/a	Yes/No
	PH Configuration	n/a	Single/Twin
	Gap From Port to Stb. PHs (If Applicable)	m	0-2.4 (0.2)
	Ratio of Dia. of Propulsor to Casing Dia.	%	10-80 (10)
Primary Propulsion	Primary Propulsion Type	n/a	Diesel/Stirling/CCST/Fuel Cell/Nuclear
	Fuel Storage Type for Fuel Cell (if Appl.)	n/a	Methanol/MH/CNF
	Max Speed (Nuclear or Non-Nuclear + Battery Boost)	Knot	15-35 (5)
	Transit Speed (Non-Nuclear)	Knot	6-12 (1)
	Max Speed (Non-Nuclear)	Knot	11-20 (1)
Secondary Propulsion	Max Speed Achievable on Batteries Only	Knot	1-10 (1)
	Secondary Propulsion Type	n/a	Diesel/Stirling/CCST/Fuel Cell
	O2 Storage Type (If Applicable)	n/a	Internal/External/HTP
	Fuel Storage Type for Fuel Cell (If Appli.)	n/a	Methanol/MH/CNF
	Fuel Cell Type (If Applicable)	n/a	APEM/PEM/AFC/PAFC
UUV Payload	UUV Role	n/a	Sea Denial/Coastal Strike/CAP
	UUV Category A LARS Type	n/a	Single Interface/Self-Contained
	UUV Category A Stowage Type	n/a	Int./Ext./Ext. & ARM Int. Garage
	Number of Category A UUVs	n/a	4-12 (1)
	Displacement of Category A UUV	te	5-25 (5)
Electronic Payload	Passive Bearing Sonar Level	n/a	Level 0-5 (1)
	Passive Ranging Sonar Level	n/a	Level 0-2 (1)
	Passive Class Active Bearing Sonar Level	n/a	Level 0-2 (1)
	Radar Level	n/a	Level 0-2 (1)
	EW Level	n/a	Level 0-5 (1)
	CMS Level	n/a	Level 0-7 (1)
	Communications Level	n/a	Level 0-4 (1)
Traditional Weapons Payload	CM System Level	n/a	0/6/12 Band fish
	ASuW Level	n/a	0/2/6/16 ASM
	ASW Level	n/a	0/4/8/20 HWT
	AAW Level	n/a	None/Muraena Gun/ IDAS Missile
	LA Level	n/a	0/6/20 TLAM
	Mine Level	n/a	0/4/12
	Torpedo Tube Number (If Applicable)	n/a	2/4/6
	Torpedo Launch System Level	n/a	None/Int./Ext. (Single Shot)/ Ext.
	LA Launch System Level (If applicable)	n/a	Torp. Tube/Single VLS/ 'Baby' MAC/ MAC
Masts	Communications Mast	n/a	Yes/No
	Optronic Mast	n/a	0/1/2
	Radar Mast	n/a	Yes/No
	Triple M (Modular Multipurpose Mast)	n/a	Yes/No
Crew	Days on Patrol	Days	40-100 (10)
	Number of Watches	n/a	2-3 (1)
	Overhead in Watches	%	0-50 (10)

D.3 DESIGN OF A BASIC SUBMARINE

The Basic Submarine Design was intended to be a poorly performing (as defined by MoTPC) but naval architecturally balanced submarine design at a concept level to benchmark against other submarine designs, calculating their performance differentials.

Table D2 – The Basic Submarine Design

Category	Characteristic	Value	Units
Structure	Displaced Weight (Submerged)	5000	te
	RoB	10	%
	DDD	100	m
	LOA	89	m
	Diameter PH	9.8	m
	Length PH	62	m
	Aspect Ratio (Length: Width)	9.08	
	Number of Decks	3	
Move	Max Speed	20	Knots
	Transit Speed on Diesels ("Limp to Friendly Base")	4	Knots
	I.R. on Diesel Power	26	%
	Hover Ability?	No	
	Range without Nuclear Propulsion	2000	nm
Propulsion/Power	Number of Nuclear Reactors	1	
	Number of Steam Turbines	2	
	Number of Turbo Generators	2	
	Number of Condensers	2	
	Non-Nuclear Power Type	Diesel	
	Number of DG	2	
	Thermal Power for Nuclear Reactors (30% efficient)	18.6	MW
	Max Effective Power at Shaft	5.59	MW
	Max Allowable Hotel Power	0.5	MW
	Max Combined Power for 2 DGs	1.5	MW
Payload	Number of Torpedoes	6	
	Number of Torpedo Tubes	2	
	Number of TLAM	0	
	Number of Mines	0	
Manning	Total	70	
	Number of Officers	15	
	Number of Senior Rates	21	
	Number of Junior Rates	34	

D.4 ‘OPTIMISING’ THE NUMBER OF SYSTEM GROUPS

The likely uneven distribution of Top-Level Input Variables (TLIVs) to SGs, due to reasons of suitability, mean the ‘optimised’ number of SGs can only be considered approximate. However, an improvement can be made over an arbitrary distribution of TLIVs for SGs. There was seen to be a trade-off between a large number of SGs with fewer TLIVs per SG, resulting in a large number of combinations (i.e. points) on the overall level Pareto Front – and more TLIVs per SG leading to more SG options at the SG-level and so fewer points the overall level Pareto Front. To ‘optimise’ the distribution of TLIVs for SGs, the following equations have been derived:

$$\text{Number of SGs}=\text{Num}_{\text{SG}}$$
$$\text{Number of Top-Level Input Variables}=\text{Num}_{\text{TLIV}}$$

$$\text{(Average) Number of Options per Top – Level Input Variable}=\text{TLIV}_{\text{Option}}$$
$$\text{Estimated Number of SG-Level Pareto Front Points for each SG}=\text{SG}_{\text{Option}}$$

The (average) number of combinations per SG:

$$\text{SG}_{\text{option}} = \text{TLIV}_{\text{option}}^{\frac{\text{Num}_{\text{TLIV}}}{\text{Num}_{\text{SG}}}}$$

The number of combinations of SG-level Pareto Front points:

$$\text{SG}_{\text{option}}^{\text{Num}_{\text{SG}}}$$

Thus, the total number of calculations would be the number of combinations per SG times the number of SGs plus the number of combinations of estimated SG-level Pareto Front points:

$$\text{Total}=\text{Num}_{\text{SG}}\text{TLIV}_{\text{option}}^{\frac{\text{Num}_{\text{TLIV}}}{\text{Num}_{\text{SG}}}}+\text{SG}_{\text{option}}^{\text{Num}_{\text{SG}}} \qquad \text{[Eqn. D1]}$$

If the expression for the total number of calculations was differentiated with respect to the number of SGs and made equal to zero, the expression to find the ‘optimum’ number of calculations is:

$$\frac{\partial\text{Total}}{\partial\text{Num}_{\text{SG}}}=\text{TLIV}_{\text{option}}^{\frac{\text{Num}_{\text{TLIV}}}{\text{Num}_{\text{SG}}}}-\frac{\text{Num}_{\text{TLIV}}\text{TLIV}_{\text{option}}^{\frac{\text{Num}_{\text{IV}}}{\text{Num}_{\text{SG}}}}\ln(\text{TLIV}_{\text{option}})}{\text{Num}_{\text{SG}}}+\text{SG}_{\text{option}}^{\text{Num}_{\text{SG}}}\ln(\text{SG}_{\text{option}})=0 \qquad \text{[Eqn. D2]}$$

Equation D2 can not be solved with analytically so instead, it was solved using a numerical method. Inputting some typical values as an example (number of TLIV = 36, the number of options per input variable = six, and the number of points on the Pareto Front for each SG = 70) gave an ‘optimised’ number of SGs as approximately five. Thus, grouping the TLIVs into five SGs should result in the least amount of computation during the undertaking of the NPF approach. The construction of the equation means that the total number of required calculations is highly sensitive to the number of SGs. Hence, it was concluded that the 'optimum' number of SGs should be used in creating the SG-level and Notional Pareto Fronts, and it is not acceptable to use a 'standard' number for all applications of SUPERB.

D.5 COST CALCULATION

The assessed cost of a design in SUPERB is for the unit production cost (UPC) and is calculated using UCL's concept costing metric, which is used in the UCL Submarine Design Course (2014). The metric generates a cost, which is considered believable but not necessarily accurate. The cost is given in "UCL Pounds", which roughly equate to Pound Sterling. The metric assigns a fixed cost per tonne for each of the weight groups stated in Table D3.

Table D3 – Weight Breakdown Groups (1 Digit)

Weight Group
1. Structures
2. Propulsion Systems
3. Electrical Services
4. Control & Communications
5. Boat Services
6. Outfit & Furnishings
7. Armaments & Pyrotechnics
8. Fixed Ballast
9. Variable Items

A modification factor is applied to special equipment, which is considered expensive/inexpensive relative to its weight group derived cost. An example of such equipment would be a nuclear reactor.

D.6 DESIGN MARGINS

The design margins used by SUPERB are stated in Table D4 and have been adopted from Harris, et al (2009). These have been given for a 'traditional' design – i.e. where the designer has some experience designing similar vessels. For the novel technologies, such as UUVs, additional margins have been assumed (see Table F1) to reflect the increased level of uncertainty for defining weight and volumes.

Table D4 – Design Margins for Weight and Volume Adopted SUPERB

Weight Group	Weight Margin (%)	Volume Margin (%)
1. Structures	5	1
2. Propulsion Systems	5	10
3. Electrical Services	3	7
4. Control & Communications	3	6
5. Boat Services	5	5
6. Outfit & Furnishings	4	7
7. Armaments & Pyrotechnics	3	6
8. Fixed Ballast	0	0
9. Variable Items	4	5

The mathematical modelling of the geometry additionally adds an extra margin of the volume of the compartment to allow for volume lost when a compartment is fitted into a submarine deck. The compartment is modelled as a cuboid and the volume bounded by a circular pressure hull and the decks are not – hence the additional volume. The additional volumetric margin uses the ratios of useable volume to the total volume within a pressure hull, given by Figure 7.1 in Burcher & Rydill (1994). During the validation work of comparing SUPERB-generated submarines, against their replica versions in Paramarine, it was demonstrated that this addition of volume was appropriate and correct. For example, the nuclear reactor compartment for the Trafalgar SSN produced by SUPERB was within 5% difference of its Paramarine produced version.

D.7 SUPERB BALANCING PROCEDURE

D.7.1 TOP LEVEL SCHEMATIC

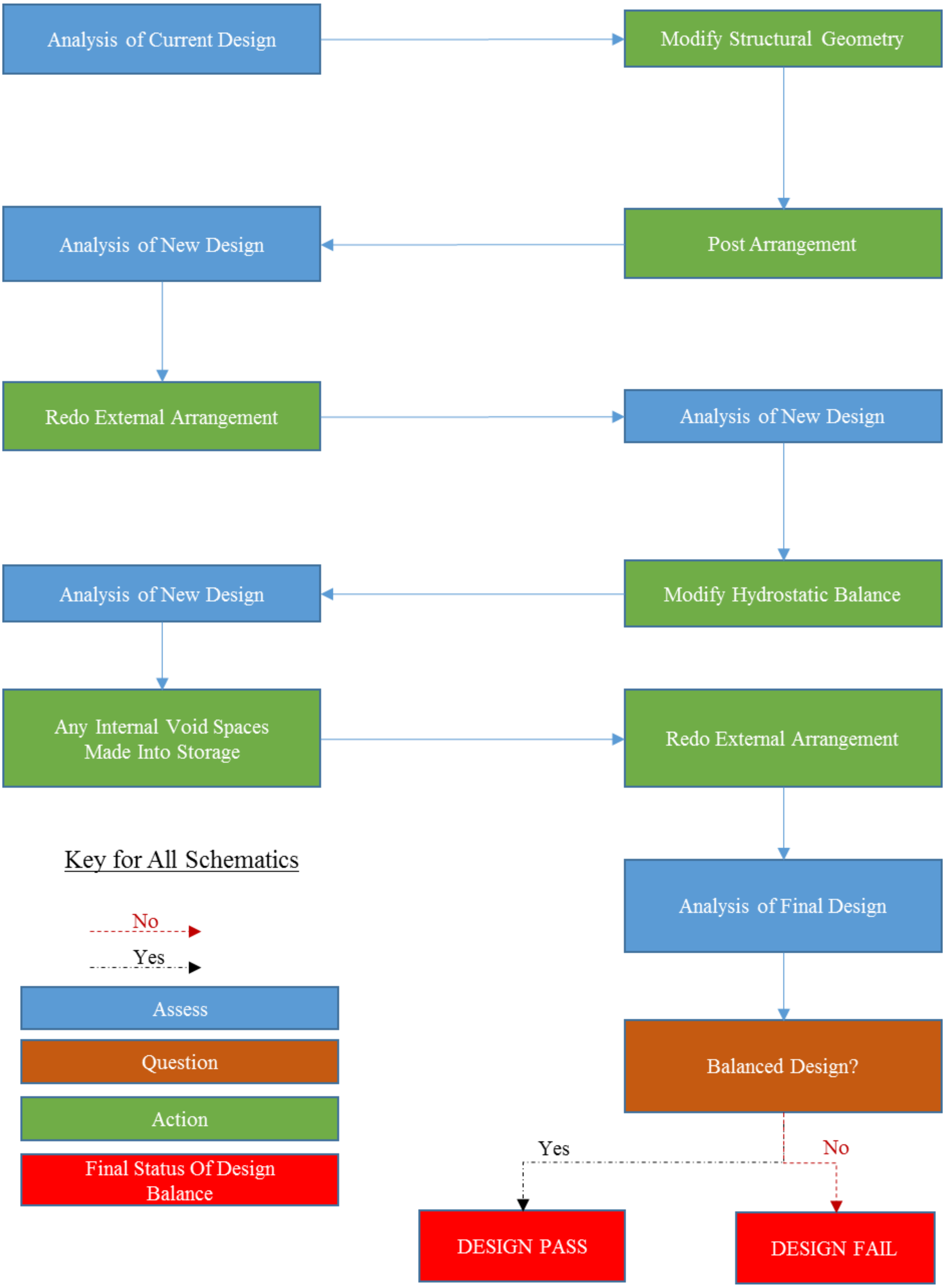

Figure D2 – Top-Level Schematic of SUPERB'S Balancing Procedure

D.7.2 TIDY ALGORITHM SCHEMATIC

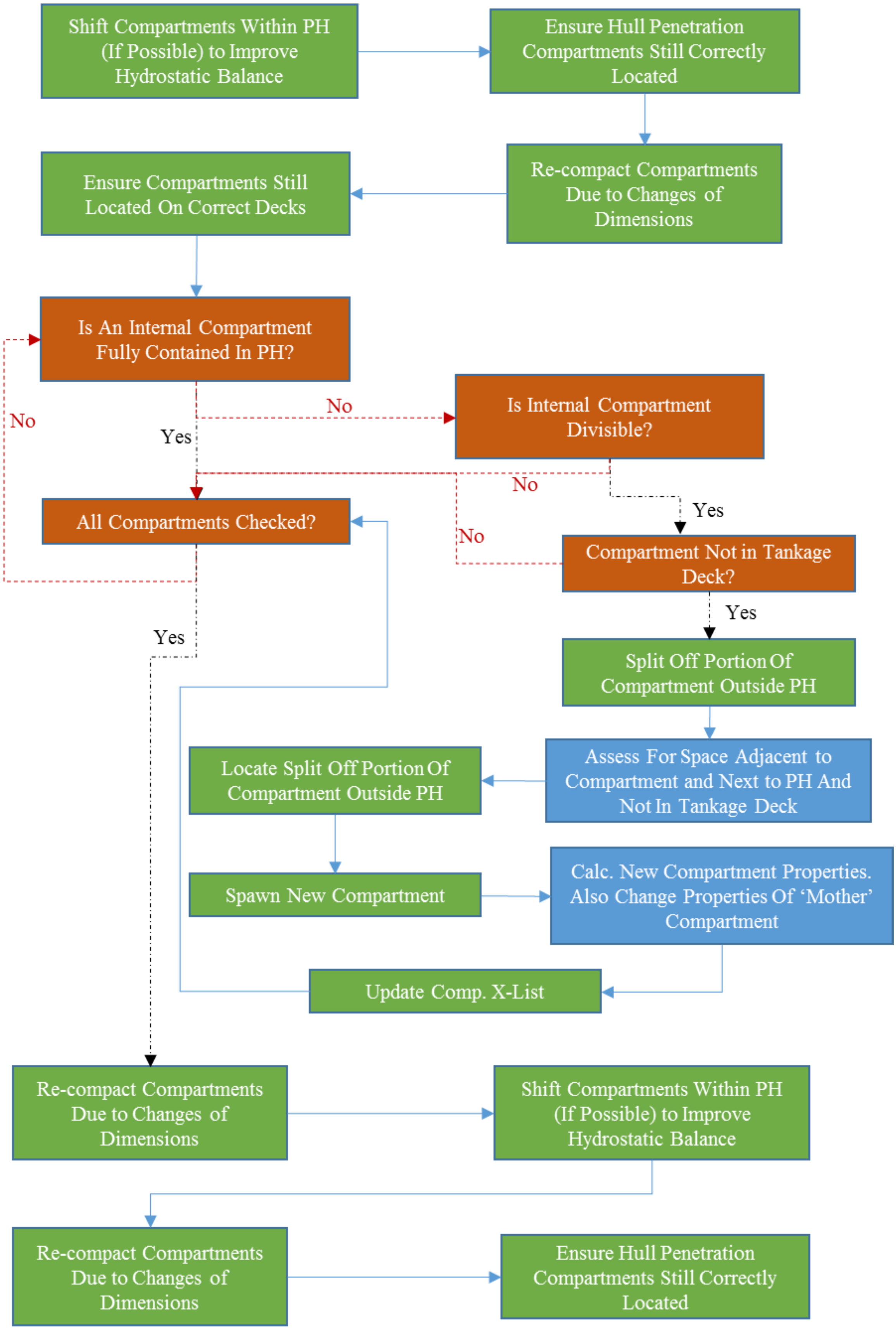

Figure D3 – SUPERB's Post-Arrangement Algorithm Schematic

D.7.3 STRUCTURAL GEOMETRY MODIFICATION ALGORITHM

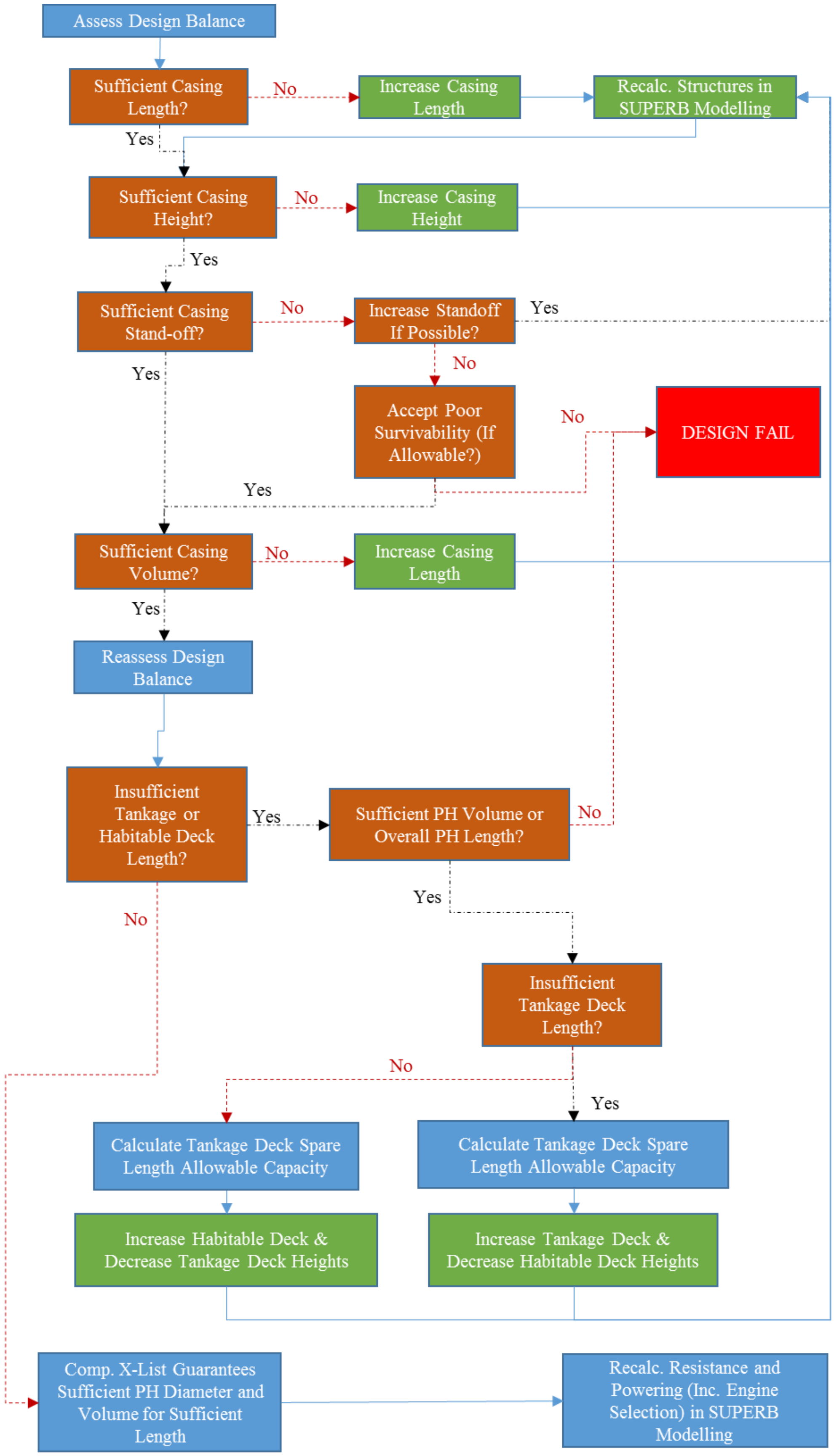

Figure D4 – SUPERB's Balancing Structural Geometry Algorithm Schematic

D.7.4 HYDROSTATIC BALANCE MODIFICATION ALGORITHM

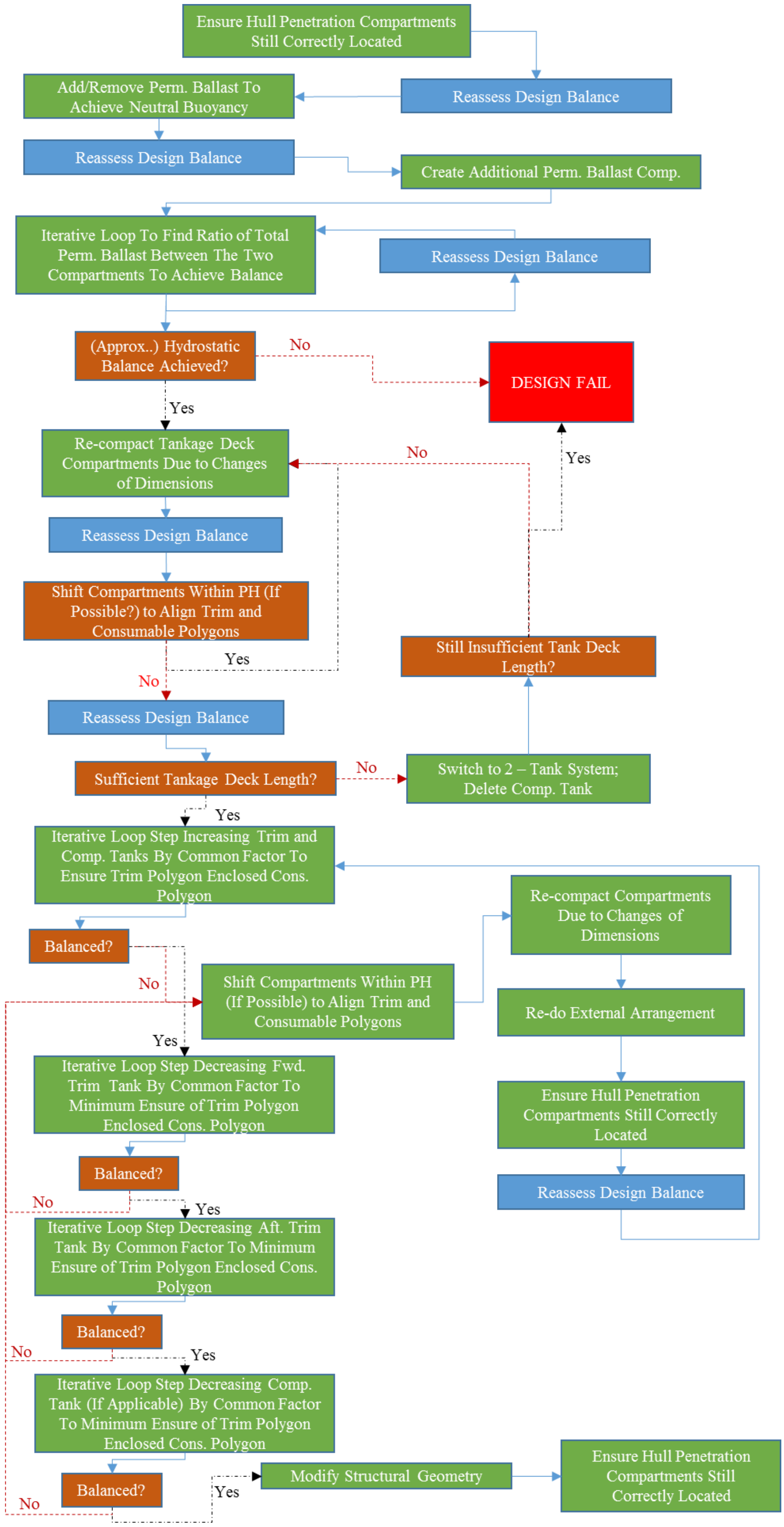

Figure D5 – SUPERB's Balancing Trim and Compensation Algorithm Schematic

D.7.5 ERROR CODES USED BY SUPERB'S ANALYSIS MODULE

Table D5 – Example of Code Errors Used by SUPERB's Analysis Module to Determine Naval Architectural Balance

Criteria	Error Code	Definition	Allowable Tolerance
Casing Volume	101	Sufficient Casing Volume Provided	2 %
Casing Height	102	Sufficient Casing Height Provided	2 %
Casing Length	103	Sufficient Casing Length Provided	2 %
Casing Width	104	Sufficient Casing Width Provided	2 %
PH Volume	201	Sufficient PH Volume Provided	2%
PH Length	202	Sufficient PH Length Provided	2.5 %
PH Length (Tankage)	203	Sufficient PH Length Provided for Tankage	2.5 %
PH Diameter	204	Sufficient PH Diameter Provided	2.5 %
Max. Speed (Primary)	301	Sufficient (Primary) Powering to Achieve Specified Maximum Speed	0.1 Knot
Transit Speed (Primary)	302	Sufficient (Primary) Powering to Achieve Specified Transit Speed	0.1 Knot
Max. Speed (Secondary)	301	Sufficient (Secondary) Powering to Achieve Specified Maximum Speed	0.1 Knot
Emergency Speed (Battery Only)	304	Sufficient (Battery) Powering to Achieve Specified Speed	0.1 Knot
Submerged Density	401	Submerged Density = 1.0275 kg/dm^3 in ST&C[1]	2 %
Trim Conditions	402	Trim Polygon Sufficiently Sized to Maintain Trim in all Design Load Conditions	5 %
Roll Submerged Stability	403	Vertical Distance Between C of B and C of G >4% of PH Diameter	0%
Pitch Submerged Stability	404	Longitudinal Distance Between C of B and C of G <2.5% Casing Length	2 Voxel Lengths (1.14 m)

D.8 VOXELS

The geometry of compartments is represented in SUPERB by being discretised into cubic voxels[2]. A voxel represents a volume in three-dimensional space. Discretisation simplifies the geometric space in which compartments can be arranged by defining each relevant dimension by an integer number of blocks. This is opposed to arranging compartments with a mixture of fractional dimensions. Thus, the

[1] ST&C – Standard Trim and Compensation Condition. This is defined in Chapter Appendix 3 of Burcher & Rydill (1994)
[2] The word "voxel" is a portmanteau of the words "volume" and "element".

computer is only required to ‘remember’ the space occupied for each dimension of a compartment as an integer number. This is a more efficient use of computer memory and hence reduces the time required to perform arrangement and subsequent geometric auditing.

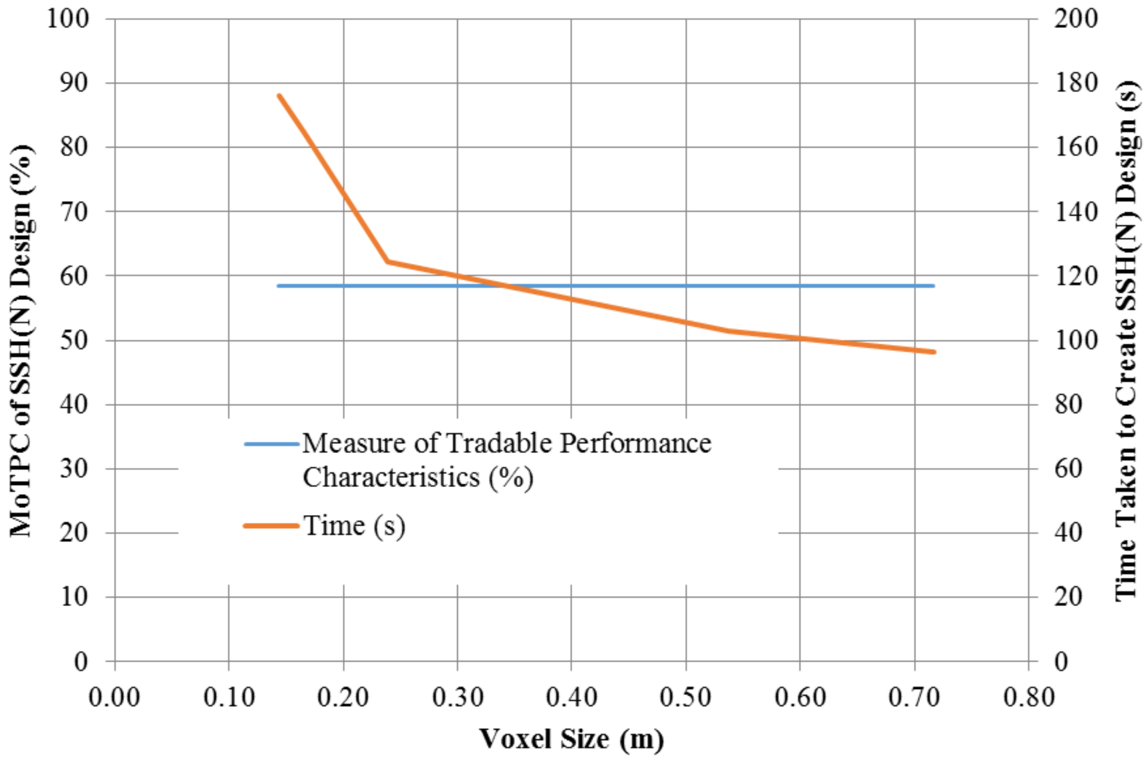

Figure D6 – Convergence Study of Voxel Dimension

A convergence study for voxel dimensions was undertaken and the results are shown in Figure D6. The method used in this study was derived from that of a convergence study that should be undertaken in an FEA (Finite Element Analysis) problem. The longest possible voxel dimension that did not affect the geometric arrangement result was identified by running the program for a range of voxel dimension values and analysing the geometric arrangements produced. It was observed that the value for the MoTPC of an SSH(N) design produced in SUPERB was only weakly dependent on voxel dimensions, but the time to achieve a solution was strongly influenced by them. There was a trade-off between smaller sized voxels, giving greater fidelity to the geometric characteristics of a compartment, and a quicker solution time caused by larger voxels, whose requirements for computer memory were reduced due to the lower fidelity. The voxel dimension considered to present the best trade-off was 0.57 m.

D.9 COMPARTMENT PROPERTIES

Each compartments' properties are defined using a format devised specifically for SUPERB. This format is illustrated in Table D6. The adoption of this format allows SUPERB to consider a varying number and type of compartments. It also makes the consideration of new compartments easy to facilitate, such as the hypothetical teleport blocks in the SST simulations in Section 5.3.

Table D6 – Compartment Properties Used in Compartment X-Listing

Property	Required or Optional for SSH(N) Arrangement in SUPERB	Example Value
Minimum Volume [m^3]	Required	30
Minimum Area [m^2]	Optional	50
Minimum Length [m]	Optional	10
Minimum Width [m]	Optional	2
Minimum Height [m]	Optional	2
Deck Driven[1] Geometry?	Required	Yes
Divisible Compartment?	Required	No
Maximum Loaded Weight [Te]	Required	50
Minimum Loaded Weight [Te]	Required	30
Unloaded Weight [Te]	Required	25
2-Digit Weight Breakdown Classification and Proportion	Required	50% to Class 6.5 25% to Class 3.2 25% to Class 3.5
Type (Logistical Effort)	Required	Stores
Group (Functional DBB)	Required	Infrastructure
Vertical Location Flexibility	Required	1 (Vertical Constraint Limited to One Direction – see Sub-subsection 4.5.4.i)

[1] Deck Driven = The geometry of the compartment is forced to occupy a single deck

APPENDIX E - PERFORMANCE MEASURES FOR THE SUPERB TOOL

NOMENCLATURE

AAW	Anti-Aircraft Warfare
ARM	Availability, Reliability and Maintenance
ASM	Anti-Ship Missile
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
C	Constant
CM	Countermeasures
CMS	Combat Management System
Comp	Compensation
DDD	Deep Dive Depth [m] (of a submarine)
D_{so}	Standoff Distance between Pressure Hull and Casing [m]
EW	Electronic Warfare
Hydro	Hydrodynamic Performance
iRisk	Indicative Risk
ISR	Intelligence, Surveillance and Reconnaissance
Kp	Hydrodynamic Hull Form Factor (As per the Propulsion Motor equation in Chapter 11.22 in Burcher & Rydill (1994))
LA	Land Attack
LAM	Land Attack Missile
iMOP	Indicative Measure of Performance
MoTPC	Measure of Tradable Performance Characteristics
RoB	Reserve of Buoyancy (Typically 10% of surfaced displacement for a military submarine) [%]
Prop	Propeller
SSLM	Submarine Launched Mobile Mine
Surv	Survive
U' Boat	Velocity on Non-Nuclear Propulsion [Knots]
U'_{Sprint}	Sprint Velocity (Non-Nuclear Propulsion) [Knots]
U'_{Trans}	Transit Velocity (Non-Nuclear Propulsion) [Knots]
U_{Max}	Maximum Velocity of Boat [Knots]
η_s	Shaft Transmission Efficiency
$\Delta_{T\&C}$	Buoyancy Capacity of Trim and Compensation Tanks [Tonnes]

E.1 INTRODUCTION

Sets of design characteristics have been chosen to ensure SG-level Pareto Front will be correctly pre-calculated, according to the protocols of the NPF approach using SUPERB. According to these protocols, every SG-level Pareto Front should be comprised of system options that are:

1. Technically conceivable
2. Non-dominated by other options for the SG

E.2 PERFORMANCE

The design characteristics have been organised to form measures of performance called Measures of Tradable Performance Characteristics (MoTPC) to meet both the protocol requirements. MoTPC is not a 'true' measure of performance, as some individual measures do not represent 'true' types of performance, but instead these individual measures are proxies for performances. For example, the reserve of buoyancy (RoB) is not in itself a type of performance; however, it does indicate a level of survivability for a design (from flooding due to damage). The MoTPC has been termed by the candidate as an indicative Measure of Performance (iMOP)

The definition of non-dominated SG options is carried out fromthe perspective of a whole boat (i.e. synthesised) performance metric and not SG-level performance metrics. The MoTPC should be selected to indicate the unbiased (synthesised) performance of a submarine design. This should ensure that while there could be multiple ways of meeting some level of whole-boat performance, MoTPC reflects a non-biased assessment method with regard to design unorthodoxy.

The rest of this appendix describes how the MoTPC is calculated. The weightings detailed in Table D7, are based on a weighting guide from Whitcomb (1998).

Table D7 – Weightings for the Calculation of the MoTPC of a Submarine Concept Exploration

		Type of Tradable Performance Characteristic							
		Speed		Skirmish		Survivability		Stealth	
		Design Characteristic	Weight	Design Characteristic	Weight	Design Characteristic	Weight	Design Characteristic	Weight
System Group	Strength	Hull Hydrodynamics	0.33			Casing Stand-off Distance	0.20	Acoustic Signature	0.20
	Strength					RoB	0.20	DDD	0.20
	Nuclear Propulsion	Propeller Efficiency	0.33					Acoustic Signature	0.20
	Nuclear Propulsion	Maximum Speed	0.22						
	Non-Nuclear Propulsion	Transit and Sprint Speeds	0.11					Indiscretion Ratio	0.20
	Non-Nuclear Propulsion					Emergency Escape on Batteries	0.20		
	Electronic Payload			Radar	0.07				
	Electronic Payload			Sonar	0.07				
	Electronic Payload			CMS & EW	0.07				
	Electronic Payload			Comms	0.07	Comms	0.20	Sonar	0.20
	Traditional Weapons Payload			ASuW & ASW	0.12				
	Traditional Weapons Payload			Mines	0.07				
	Traditional Weapons Payload			Land Attack	0.07				
	Traditional Weapons Payload			AAW	0.07				
	Traditional Weapons Payload			CM	0.04				
	UUV Payload			USGOT	0.33				
	Manning					Watch Keeping & Margin	0.20		
	Total Weight		**1.00**		**1.00**		**1.00**		**1.00**

E.3 RISK

It follows that like performance, risk could be indicated by a design's characteristics. Thus, it is conceivable to consider an indicative metric for risk (iRisk), which is related to the MoTPC. This would represent the technical and performance risks in developing a design. For example, a design using a hull form with poor hydrodynamics indicates there to be a technical risk (i.e. possibility) that such a hull-form could not make the required speed due to excessive resistance

If iRisk is considered relatable to deviation from some 'ideal' for a design characteristic, it could then be quantifiable. For example, the greater a hull form's deviation from the hydrodynamically ideal 'teardrop' form, the poorer the hullform's hydrodynamics and thus, the greater the risk that the design requires excessive power. The same weighting configuration for MoTPC was be adopted for iRisk calculation. It was concluded that a set of 'ideal' design characteristics could not be reliably defined at the concept level of granularity and thus, the iRisk was not used in any of the SSH(N) designs in the current research. However, other concept studies could conceivably use it.

E.4 STRUCTURES

E.4.1 HYDRODYNAMICS PERFORMANCE

The hydrodynamic performance equation is based on the hydrodynamic hull form shape coefficient (Kp) in the powering equation in Burcher & Rydill (1994). A value of 20 for the coefficient has been used to represent the ideal hydrodynamic 'teardrop' shape and indicative performance represented as being inversely proportional to the actual value.

$$\mathrm{MoTPC_{Hydro}} = \mathrm{C_{Hydro}} \frac{20}{\mathrm{Kp}} \qquad \text{(Eqn. E1)}$$

E.4.2 STRUCTURE SURVIVABILITY

The survivability performance is related to the 'Structures' SG and based on three individual measures: the standoff distance between casing; the compensation ability of the design; and the Reserve of Buoyancy (RoB).

$$\mathrm{MoTPC_{Surv}} = \mathrm{iMOP_{Dso}} + \mathrm{iMOP_{RoB}} + \mathrm{iMOP_{Comp}} \qquad \text{(Eqn. E2)}$$

9.3.3.vi Casing Stand-Off Distance

The standoff distance between the casing and pressure hull (D_{so}) indicates a level of survivability, as a separation between the casing and pressure hull is considered to improve the boat's chances of remaining operational after being damaged. It is also considered that effect on survivability by increasing the value for D_{so} reduces as D_{so} increases (i.e. a logarithmic relationship). Furthermore, if a boat design has a twin pressure hull, the separation distance between the two pressure hulls could have a similar effect as the D_{so}. Hence, the survivability 'performance' for standoff is calculated by:

$$MoTPC_{Dso}=\begin{cases} C_{Dso}\dfrac{\ln(D_{so}+1)}{2}, & \text{Single PH Configuration} \\ C_{Dso}\dfrac{\ln(D_{so}+D_{PH\ Gap}+1)}{2}, & \text{Twin PH Configuration} \end{cases} \qquad \text{(Eqn. E3)}$$

9.3.3.vii Reserve of Buoyancy

The Reserve of Buoyancy (RoB) has been used as a survivability attribute as a greater RoB means a larger a margin of safety in the event of flooding. Thus, the 'performance' for RoB is represented as the design RoB non-dimensionalised by an upper bound of 50% RoB.

$$MoTPC_{RoB}=C_{RoB}\frac{RoB}{0.5} \qquad \text{(Eqn. E4)}$$

E.4.3 STEALTH

9.3.3.viii Deep Diving Depth

The Deep Diving Depth (DDD) has been used as an attribute of survivability as a greater DDD means the submarine could dive deeper, reducing the probability of detection and so increasing its level of stealth. The DDD also reduced susceptibility as the submarine can out-dive lightweight torpedoes. The 'performance' for the stealth from DDD is assumed to vary linearly with an upper bound value of 1000m. This assumption due to a lack of information and it is recognised that is highly likely that this relationship is actually non-linear.

$$MoTPC_{DDD}=C_{DDD}\frac{DDD}{1000} \qquad \text{(Eqn. E5)}$$

9.3.3.ix Acoustic Signature

This 'performance' is the predicted range of a 50% chance of detection of the design submarine (moving at 6 knots) by a passive sonar, relative to SUPERB's representation of a Trafalgar class SSN travelling at 6 knots. The acoustic performance is derived from the equations for acoustic signature modelling of a submarine by the model described in Appendix G. The 'performance' for an acoustic signature of the 50% probability of range detection limit (measured in nautical miles) is non-dimensionalised relative to an upper limit of 200 nautical miles.

$$MoTPC_{Signature}=C_{Signature}\frac{D_{50\%\ Sub}}{200} \qquad \text{(Eqn. E6)}$$

E.5 NUCLEAR PROPULSION

E.5.1 MAXIMUM SPEED

Maximum speed performance is relative to a 40-knot benchmark (considered an upper ceiling value). It is assumed that the relationship between performance and higher maximum speed is a linear one. This is due to the difficulty in representing the effect of maximum speed on performance.

$$MoTPC_{U\ Max}=C_{U\ Max}\frac{U_{Max}}{40} \qquad \text{(Eqn. E7)}$$

E.5.2 PROPELLER EFFICIENCY

The ‘performance’ for the propeller efficiency has been represented as the propulsive coefficient (PC) times the shaft efficiency (η_s) as described in Burcher & Rydill (1994). A linear relationship is used.

$$MoTPC_{Prop}=C_{Prop}PC\ \eta_s \qquad \text{(Eqn. E8)}$$

E.6 NON-NUCLEAR PROPULSION

E.6.1 COMBINED NON-NUCLEAR TRANSIT AND SPRINT SPEEDS

Transit speed performance is relative to a 10-knot benchmark (considered an upper ceiling value). Similar to defining the model for the performance concerning maximum speed, non-nuclear speeds are difficult to model and so a simple linear model is used. Maximum speed performance is relative to a 20-knot benchmark (considered an upper ceiling value).

$$MoTPC_{U'_{Speeds}}=C_{U'\ Speeds}\frac{\left(\frac{U'_{Trans}}{10}+\frac{U'_{Sprint}}{20}\right)}{2} \qquad \text{(Eqn. E9)}$$

E.6.2 BATTERY POWERED ESCAPE

Emergency escape on batteries only is relative to a 10-knot benchmark (considered an upper ceiling value). This is a simple linear model as it is assumed the faster the boat can escape danger, the better its chances of survival.

$$MoTPC_{U_{Esc}}=C_{U_{Esc}}\frac{U_{Esc}}{10} \qquad \text{(Eqn. E10)}$$

E.6.3 INDISCRETION RATIO (IR)

This ‘performance’ is based on the IR for the primary propulsion power source at transiting speed. It has been assumed that the probability of detection (i.e. a measure of stealth) is proportional to snorting time.

$$MoTPC_{IR}=C_{IR}\,(1\text{-}IR) \qquad \text{(Eqn. E11)}$$

E.7 ELECTRONIC PAYLOAD

E.7.1 COMMUNICATIONS

The ‘performance’ of the communications room is based on discrete performance values for the options detailed in UCL’s Submarine Design Procedure (2012) for its post-graduate course.

E.7.2 RADAR

The ‘performance’ of the radar is based on discrete performance values for the options detailed in UCL’s Submarine Design Procedure (2012) for its post-graduate course.

E.7.3 COMBAT MANAGEMENT SYSTEM & ELECTRONIC WARFARE

The ‘performance’ of the Combat Management System (CMS) and Electronic Warfare (EW) in the Command and Control (C2) room is based on discrete performance values for the options detailed in UCL’s Submarine Design Procedure for its post-graduate course (2012).

E.7.4 SONAR

This is the predicted distance of a 50% chance detection of SUPERB’s Trafalgar class submarine travelling at 6 knots by a passive sonar relative to an upper limit of 2000 nautical miles. This limit was selected to ensure it would be higher than all likely detection ranges. The acoustic performance is derived from the equations for acoustic signature modelling of a submarine in Appendix G.

$$MoTPC_{Sonar}=C_{Sonar}\left(1\text{-}\frac{D_{50\%\ T\text{-}Class}}{2000}\right) \qquad \text{(Eqn. E12)}$$

E.8 WEAPONS

E.8.1 COUNTERMEASURES

This MoTPC is based on a linear scale for a number of Bandfish countermeasures. The maximum number (i.e. an upper limit) of Bandfish carried by a submarine has been taken as 16. In place of any detailed operational analysis (OA), a simple linear model has been assumed. Hence:

$$MoTPC_{CM}=C_{CM}\frac{Num_{CM}}{16} \qquad \text{(Eqn. E13)}$$

E.8.2 ANTI-SURFACE SHIP AND ANTI-SUBMARINE WARFARE

Based on a linear scale for the number of anti-ship missiles (ASM), heavyweight torpedoes (HWT) and torpedo tubes. The linearity of trade-offs between ASMs and HWT has been assumed due to a lack of relevant information. It is acknowledged that additional HWTs can often be preferred to ASMs. The number of weapons is an indicative performance of the submarine in terms of the number of targets it can engage. The number of torpedo tubes points to a performance of the submarine to engage a number of targets simultaneously, or more usually, increasing the chances of a successful engagement as it is harder to evade multiple incoming weapons. ASuW and ASW are considered together due to the use of common torpedo tubes. The maximum number (i.e. an upper limit) of ASMs carried by a submarine has been taken as 16. Maximum number (i.e. an upper limit) of HWTs carried by a submarine has been taken as 20. Maximum number (i.e. an upper limit) of torpedo tubes on a submarine has been taken as six. Hence:

$$\mathrm{MoTPC}_{\mathrm{ASW\&ASuW}}=(\mathrm{C}_{\mathrm{ASW\&ASuW}})\left(\frac{\mathrm{Num}_{\mathrm{ASM}}}{16}+\frac{\mathrm{Num}_{\mathrm{HWT}}}{20}+\frac{\mathrm{Num}_{\mathrm{Torp\ Tube}}}{6}\right) \qquad \text{(Eqn. E14)}$$

E.8.3 MINES

Maximum number (i.e. an upper limit) of SLMMs on a submarine has been taken as 12. Hence, based on a linear scale, the model for mine performance is:

$$\mathrm{MoTPC}_{\mathrm{Mine}}=(\mathrm{C}_{\mathrm{Mine}})\left(\frac{\mathrm{Num}_{\mathrm{SLMM}}}{12}\right) \qquad \text{(Eqn. E15)}$$

E.8.4 ANTI-AIRCRAFT WARFARE

The value for the AAW performance is based on an estimation, due to a lack of detailed and accessible OA. AAW in SUPERB can be provided by an IDAS missile or a light cannon (e.g. a Mauser BK-27) mounted in a multi-purpose “Triple M” mast (Gabler Naval Technology, 2008).

$$\mathrm{MoTPC}_{\mathrm{AAW}}=\begin{cases} 0, & \text{No AAW} \\ 0.40\mathrm{C}_{\mathrm{AAW}}, & \text{Mureana Gun in Triple M Mast} \\ 1.00\mathrm{C}_{\mathrm{AAW}}, & \text{IDAS in Torpedo Tube} \end{cases} \qquad \text{(Eqn. E16)}$$

E.8.5 LAND ATTACK

Multiple possible launch systems for the Tomahawk Land Attack Missile (TLAM) are considered in SUPERB. However, the effect on the overall boat performance of the TLAM launch system options is hard to quantify without detailed OA. It was assumed that all launch system options can provide a similar number of simultaneous launches of TLAMs, and do not place a restriction on the number of TLAMs carried by a submarine. This has been assumed to imply there is no effect on the land attack performance by the choice of TLAM launch system. Thus, the land attack ‘performance’ is based solely on a linear scale for the number of TLAMs carried, which is indicative of the number of targets that could be engaged by a submarine. An upper limit on the number of TLAMs carried has been set at 20.

$$MoTPC_{LA}=C_{LA}\frac{Num_{LAM}}{20} \qquad \text{(Eqn. E17)}$$

E.9 UUV PAYLOAD

The performance of the UUV payload is based on the results that have already been calculated by the UUV Sensor Grid Optimisation Tool (USGOT) simulations in Appendix C.

E.10 MANNING

Manning has been assumed to indicate a measure of crew redundancy to perform all the submarine’s functions. The ‘performance’ is represented as the design crew level relative to a maximum three-watch and 50% margin. This is an indicative measure and not a true assessment of crew redundancy, as it is a crude calculation the crew as a whole and does not take into account the intricacies of any command or work breakdown structure for the crew. Hence:

$$MoTPC_{Manning}=C_{Manning}\frac{Num_{Watches}(1+Overhead)}{3} \qquad \text{(Eqn. E18)}$$

APPENDIX F - MODELLING AND ASSUMPTIONS OF EQUIPMENT AND COMPARTMENTS USED IN SUPERB[1]

NOMENCLATURE

AFC	Alkaline Fuel Cell
APEM	Advanced Proton Exchange Membrane (A type of fuel cell technology)
ATP	Air Turbine Pump
BC_{Fin}	Block Coefficient for Bridge Fin
$Casing_{End\ Ratio}$	Ratio of Pressure Hull Diameter to Distance between of End of Pressure Hull and End of Casing
CCST	Closed Cycle Steam Turbine
CM	Countermeasure
CME	Countermeasure Ejector
CMS	Combat Management System
CNF	Carbon Nanofiber
CO	Commanding Officer
Comms	Communications
$Comp_{HP\ Air}$	High Pressure Air Compressor Capacity [m^3/hr]
CT	Compensation Tank
D	Diameter [m]
$\overline{D_{Aretzen}}$	Vector of Optimal Pressure Hull Diameters as Suggested by Aretzen [m] (Arentzen & Mandel, 1960)
D_{ATP}	Diameter of an Air Turbine Pump [m]
D_{ave}	Average Casing Diameter [m]
DG	Diesel Generators
DH	Accessible Height of a (Habitable) Deck [m]
D_{MG}	Diameter of Motor Generator [m]
D_{Motor}	Diameter of Main Electrical Motor [m]
D_{PH}	Diameter of Pressure Hull [m]
D_{rc}	Diameter of Reactor Compartment [m]
D_{so}	Standoff Distance between Pressure Hull and Casing [m]
DWEO	Deputy Weapons Engineering Officer
E	Energy [MWhr] (MWhr is used as the unit of energy instead of joules for Submarine Equipment for reasons of simplicity)
E_{Cell}	Energy Stored in a Single Battery Cell [MWhr]
E_{Dis}	Energy Discharged per Cell [MWhr]
E_{Esc}	Total Required Energy to be provided by Batteries [MW]
E_{fuel}	Energy of Fuel to be Stored [MW]
Esc_{Dist}	Distance to Escape Danger of Battery Power Only [nm]
F’	Total Flow Rate in Secondary Circuit of Reactor [Tonnes/Hour]
F'_{ST}	Flow Rate of Water to Steam Turbine(s) [Tonnes/Hour]

[1] Contents of this Appendix have also been included in a (commercially sensitive) report as part of a consultancy project for Babcock International entitled “UCL Research for Babcock on UUV Hosting Submarine Concepts for the SEA 1000 Project”.

F'_{TG}	Flow Rate of Water to Turbo Generator(s) [Tonnes/Hour]
FOS_{PH}	Factor of Safety for Pressure Hull Strength (to resist collapse) at Deep Dive Depth
g	Gravitational Acceleration (Equal to 9.81) [m/s^2]
GT	Gas Turbine
H	Height [m]
HEDB	High Energy Density Batteries
$H_{Gear\&Clutch}$	Height of Combined of Gearbox and Clutch [m]
H_{PH}	Total Height of a (Habitable) Deck in Pressure Hull
H_{TG}	Height of Turbo Generator(s) [m]
H_{Top}	Height of Casing Section above Cylinder Section of Casing (Excluding bridge fin) [m]
HTP	High Test Peroxide
$H_{Unavailable}$	Unavailable/Inaccessible Height of a (Habitable) Deck [m] (Typically taken up by equipment such as power cables and hydraulic pipes)
IDAS	Interactive Defence and Attack System for Submarines
I_{max}	Maximum Charging Current [A]
IR'_{Sprint}	Indiscretion Ratio while Sprinting on Non-Nuclear Propulsion
IR'_{Trans}	Indiscretion Ratio while Transiting on Non-Nuclear Propulsion
IR_{Esc}	Indiscretion Ratio for Escape on Battery Power Only
JR	Junior Rates
K_{Batt}	Proportionality Coefficient in Battery Discharge Equation
K_{mbte}	Permeability of Main Ballast Tanks
Kp	Hydrodynamic Hull Form Factor (As per the Propulsion Motor equation in Chapter 11.22 in Burcher & Rydill (1994))
$K_{Trim\&Comp}$	Permeability and Ullage of Trim and Compensation Tanks
L_{ae}	Length of Aft End of Casing (From pressure hull aft end to tip of stern) [m]
$L_{Cat\ A\ UUV}$	Length of a Category A MUV/UUV [m]
L_{cond}	Length of Main Propulsion Condenser(s) [m]
L_{cyl}	Length of Cylindrical Section of each Pressure Hull [m]
L_{fe}	Length of Forward End of Casing (From pressure hull forward end to tip of bow) [m]
$L_{Flank\ Array}$	Length if Flank Array [m]
L_{MG}	Length of Motor Generator [m]
L_{Motor}	Length of Main Electrical Motor [m]
LOA	Overall Length of Submarine [m]
L_{PH}	Total Length of Pressure Hull [m]
L_{rc}	Length of Reactor Compartment [m]
L_{ST}	Length of Steam Turbine(s) [m]
L_{SW}	Length of Main Switchboard [m]
L_{TG}	Length of Turbo Generator(s) [m]
MAC	Multiple All-Up-Round Canister (A type of submarine vertically launched weapon container system)
MBT	Main Ballast Tank
MCC	Mission Control Compartment (Specialist area dedicated to the command & control of deployed payload and/or personnel)
MEO	Marine Engineering Officer
MG	Motor Generator
MH	Metal Hydride (A form of hydrogen storage)
N	Rotational Speed of the Propeller [revolutions/s]
n_{Batt}	Exponent Coefficient in Battery Discharge Equation

Num	Quantity
Num_{ASM}	Number of Anti-Ship Missiles
Num_{c}	Number of Battery Cells
$Num_{Cat\ A}$	Number of Category A UUV/MUVs
$Num_{Cat\ A\ Men}$	Number of Personnel Maintaining Category A MUV/UUVs (Per watch)
$Num_{Cat\ B}$	Number of Category B UUVs
$Num_{Cat\ B\&C\ Men}$	Number of Personnel Maintaining Category B and C UUVs (Per watch)
$Num_{Cat\ C}$	Number of Category C UUVs
Num_{CISE}	Number of Computer Information Science and Engineering Officers (Per watch)
Num_{CM}	Number of Countermeasures
$Num_{CM\ Stow\ Bank}$	Number of Countermeasure Stowed and Launcher Banks
$Num_{Comm.\ Masts}$	Number of Communications Masts
Num_{Comms}	Number of Personnel for Communications
$Num_{Complement,\ C2\ Rm}$	Complement Number in C2 Room
$Num_{Complement,\ Comm\ Rm}$	Complement Number in Communications Room
$Num_{Complement,\ MCC\ Rm}$	Complement Number in MCC Room
$Num_{Console,\ C2\ Rm}$	Number of Consoles in C2 Room
$Num_{Console,\ Comm\ Rm}$	Number of Consoles in Communications Room
$Num_{Console,\ MCC\ Rm}$	Number of Consoles in MCC Room
$Num_{Console.\ Masts}$	Number of Consoles (in C2 Room) Required for the Masts
$Num_{CPU,\ C2\ Rm}$	Number of CPUs in C2 Room
$Num_{CPU,\ Comm\ Rm}$	Number of CPUs in Communications Room
$Num_{CPU,\ MCC\ Rm}$	Number of CPUs in MCC Room
$Num_{CPU.\ Masts}$	Number of CPUs for the Masts
Num_{Decks}	Number of (Habitable) Decks
Num_{DMEO}	Number of Deputy Marine Engineering Officers
Num_{DWEO}	Number of Deputy Weapons Engineering Officers
$Num_{Elect.\ Sensor}$	Number of Personnel for Electronic Sensors
$Num_{Engines}$	Number of Engines (Both nuclear and non-nuclear)
$Num_{Exh\ Masts}$	Number of Exhaust Masts
Num_{HWT}	Number of Heavyweight Torpedoes
$Num_{Int\ Masts}$	Number of Air Intake Masts
Num_{LAM}	Number of Land Attack Missiles
$Num_{Manning}$ Total	Number of Personnel on Boat
Num_{MEO}	Number of Marine Engineering Officers
Num_{Mine}	Number of Mines
$Num_{Non\ Nuke\ Engine}$	Number of Non-Nuclear Engines
Num_{Nuke} Total	Number of Nuclear Reactors
$Num_{Officers}$	Number of Officers
$Num_{Optronic\ Masts}$	Number of Optronic Masts
$Num_{Payload}$	Number of Personnel for C2 of Payload (Traditional and UUV)
Num_{PH}	Number of Pressure Hulls
$Num_{RadarMasts}$	Number of Radar Masts
$Num_{Reactors}$	Number of Reactors
Num_{Sonar}	Number of Personnel for Sonars
Num_{TG}	Number of Turbo Generators
$Num_{Torp\ Men}$	Number of Men Maintaining Torpedoes (Per watch)
$Num_{Torp\ Tube}$	Total Number of Torpedo Tubes

$Num_{Torp\ Tube\ Bank}$	Number of Torpedo Tube Banks
$Num_{Triple\ M}$	Number of Triple M Masts
$Num_{Warfare}$	Total Number of Personnel for Warfare Operations (Including officers)
Num_{Watch}	Number of Watches per 24 Hours
Num_{WE}	Number of Weapons (Including UUVs) Engineering (Per watch)
Num_{WEO}	Number of Weapons Engineering Officers
P	Power [MW]
P'_{Sprint}	Average Sprinting Propulsive Power on Non-Nuclear Propulsion [MW]
P'_{Trans}	Average Transiting Propulsive Power on Non-Nuclear Propulsion [MW]
P_{2nd}	Thermal Power in Secondary Circuit of Each Reactor [MW]
PAFC	Phosphoric Acid Fuel Cell (A type of fuel cell technology)
PC	Propulsive Efficiency Coefficient
$P_{CH\ Esc}$	Charging Power for Each Cell following Escape on Battery Power Only [MW]
P_{CWP}	Required Cooling Power of Chilled Water Plant [MW]
PEM	Proton Exchange Membrane (A type of fuel cell technology)
PH_{Gap}	Clearance between Adjacent Pressure Hulls (If applicable) [m]
P_{Hotel}	Hotel Power [MW]
$P_{Non\ Nuke}$	Total Non-Nuclear Power [MW]
$P_{Non\ Nuke\ Engine}$	Non-Nuclear Engine Power [MW]
P_{Req}	Required Total Power of Reactor(s) [MW]
$P_{req.\ Batt}$	Total Required Power to be provided by Batteries [MW]
$P_{shaft\ eff.\ max}$	Effective Shaft Power Delivered by Propeller(s) for Maximum Speed [MW]
$P_{shaft\ req.\ esc}$	Effective Shaft Power Delivered by Batteries for U_{Esc} [MW]
$P_{shaft\ req.\ esc}$	Required Shaft Power Delivered from Batteries for U_{Esc} [MW]
$P_{shaft\ req.\ max}$	Required Shaft Power Delivered from Engine(s) for Maximum Speed [MW]
P_{ST}	Power from Main Steam Turbine(s) [MW]
P_{TG}	Power from Main Turbo Generator(s) [MW]
$P_{TG'}$	Required Power from Turbo Generators for Non-Propulsive Loads [MW]
P_{Ther}-	Required Thermal Power of Reactor(s) [MW]
PWR	Pressurised Water Reactor (The most common type of nuclear reactor)
R	Resistance of Hull [MW]
$Ratio_{Comp}$	Ratio of Displaced (Surfaced) Volume used for Compensation
$Ratio_{Dprop:D}$	Ratio of Propeller Diameter to Casing Diameter
$Ratio_{L:D}$	Ratio of Casing Length to Diameter (i.e. the aspect ratio)
$Ratio_{Trim}$	Ratio of Displaced (Surfaced) Volume used for Trim
$Ratio_{Trim\&Comp}$	Combined Ratio of Displaced (Surfaced) Volume used for Trim and Compensation
RoB	Reserve of Buoyancy (Typically 10% of surfaced displacement for a military submarine) [%]
SSE	Submerged Signal Ejector
SR	Senior Rates
SSLM	Submarine Launched Mobile Mine
t	Thrust Deduction
T	Time [Hours]
$T'_{CH\ Sprint}$	Time to Recharge Batteries while Sprinting on Non-Nuclear Propulsion [hr]
$T'_{CH\ Trans}$	Time to Recharge Batteries while Transiting on Non-Nuclear Propulsion [hr]
$T'_{sub\ Sprint}$	Maximum Time Submerged Sprinting on Non-Nuclear Propulsion [hr]
$T'_{sub\ Trans}$	Maximum Time Submerged Transiting on Non-Nuclear Propulsion [hr]
T'_{Trans}	Transit Time to Nearest Friendly Port (Non-Nuclear Propulsion) [hr]

T_{Batt}	Maximum Time Allowable on Battery Power Only [Hours]
$T_{CH\ Esc}$	Charging Time for Each Cell following Escape from Danger on Battery Power Only [hr]
$te_{Cat\ A\ HY80}$	Thickness of HY80 Steel Pressurised Launch Tube for Category UUV/MUV [m]
$te_{PH\ HY80}$	Thickness of Pressure Hull Wall (made from HY80 Steel) [m]
$T_{sub\ Esc}$	Maximum Time Submerged for Escape on Battery Power Only [hr]
TT	Trim Tank
U’	Boat Velocity on Non-Nuclear Propulsion [Knots]
U'_{Sprint}	Sprint Velocity (Non-Nuclear Propulsion) [Knots]
U'_{Trans}	Transit Velocity (Non-Nuclear Propulsion) [Knots]
U_{Max}	Maximum Velocity of Boat [Knots]
V	Volume [m^3]
V'_{Comp}	Floodable Compensation Tank Volume [m^3]
V'_{Trim}	Floodable Trim Tank Volume [m^3]
$V'_{Trim\&Comp}$	Floodable Trim and Compensation Tanks Volume [m^3]
$V_{21''}$	Volume of 21 Inch Diameter Torpedo Tube [m^3]
v_a	Velocity of Inflow Water to Propeller [knots]
V_{ae}	Volume of Aft End of Casing [m^3]
V_{Batt}	Total Volume of Batteries [m^3]
V_{bh}	Floodable Volume between Cylinder Sections of Casing and Pressure Hull(s) [m^3]
$V_{C2\ Rm}$	Volume of C2 Room [m^3]
$V_{Cabinet}$	Volume of a Cabinet [m^3]
$V_{Cat\ A\ LARS}$	Volume of Total Launch and Recovery System(s) for Category A MUV/UUVs [m^3]
$V_{Cat\ A\ Stow}$	Volume of Total Required Stowage for Category A MUV/UUVs [m^3]
$V_{Cat\ A\ Tube}$	Volume of Pressurised Launch Tube for Category UUV/MUV [m^3]
$V_{Cat\ A\ UUV}$	Volume of a Category A MUV/UUV [m^3]
$V_{Cat\ B\ UUV}$	Length of a Category B UUV [m^3]
$V_{Cat\ B\&C\ LARS}$	Volume of Total Launch and Recovery System(s) for Category B and C UUVs [m^3]
$V_{Cat\ B\&C\ Stow}$	Volume of Total Required Stowage for Category B and C [m^3]
$V_{Cat\ B\&C\ Tube}$	Volume of Launch Tube for Category B and C UUVs [m^3]
V_{Comp}	Required Compensation Tank Volume [m^3]
$V_{Console}$	Volume of a Console [m^3]
V_{fe}	Volume of Forward End of Casing (Forward tip of pressure hull to tip of casing) [m^3]
V_{form}	Volume of Casing [m^3]
V_{Hover}	Hover Tank Volume (If Applicable) Volume [m^3]
V_{HWT}	Volume of Heavyweight Torpedo [m^3]
V_{IDAS}	Volume of IDAS Missile [m^3]
V_k	Floodable Volume of Casing (Excluding Bridge Fin) [m^3]
VLS	Vertical Launch (Missile) System
V_{mbte}	Required Floodable Volume of Main Ballast Tanks [m^3]
$V_{mbte,\ req}$	Required Total Volume of Main Ballast Tanks [m^3]
$V_{mbte,\ spare}$	Un-flooded Volume of Main Ballast Tanks [m^3]
V_{mc}	Minimum Volume of Machinery Compartment(s) [m^3]
$V_{Perm\ Ballast}$	Volume of Permanent Ballast [m^3]
V_{PH}	Volume of Pressure Hull [m^3]
V_{rc}	Volume of Each Reactor Compartment [m^3]
V_{SLMM}	Volume of Submarine Launched Mobile Mine [m^3]
V_{ST}	Volume of Steam Turbine (s) [m^3]

$V_{Store\ UUV}$	Storage Volume of a MUV/UUV [m^3]
V_{surf}	Surfaced Volume of Displaced Water [m^3]
V_{SW}	Volume of Switchboard [m^3]
V_{TLAM}	Volume of Tomahawk Land Attack Missile [m^3]
V_{Top}	Floodable Volume above Cylinder Section of Casing (Excluding bridge fin) [m^3]
$V_{Torp\ Stow}$	Total Volume of Torpedo (and other weapons) Stowage Compartment [m^3]
V_{Trim}	Required Trim Tank Volume [m^3]
V_{UUV}	Volume of a MUV/UUV [m^3]
$V_{Weapon\ Payload}$	Total Volume Weapons Payload [m^3]
W	Weight [Tonne]
w	Width [m]
$W_{21”}$	Weight of 21 Inch Diameter Torpedo Tube [Tonne]
$W_{21”\ Tube\ Equip}$	Weight Launch Equipment for of 21 Inch Diameter Torpedo Tube [Tonne]
W_{ATP}	Weight of Air Turbine Pump [Tonne]
$W_{ATP\ Sys\&Air}$	Weight of Air and System Equipment Attached to an Air Turbine Pump [Tonne]
$W_{Bandfish}$	Weight of a Bandfish Countermeasure [Tonne]
W_{Batt}	Total Weight of Batteries [Tonne]
$W_{C2\ Rm}$	Weight of C2 Room [Tonne]
$W_{Cabinet}$	Weight of a Cabinet [Tonne]
W_{cas}	Weight of Casing [Tonnes]
$W_{Cat\ A\ Ind\ LARS}$	Weight of Individual Launch and Recovery System for Category A MUV/UUVs [Tonne]
$W_{Cat\ A\ LARS}$	Weight of Total Launch and Recovery System(s) for Category A MUV/UUVs [Tonne]
$W_{Cat\ A\ Payload}$	Weight of Total Category A MUV/UUVs [Tonne]
$W_{Cat\ A\ Stow}$	Weight of Total Required Stowage for Category A MUV/UUVs [Tonne]
$W_{Cat\ A\ Tube}$	Weight of Pressurised Launch Tube for Category UUV/MUV [Tonne]
$W_{Cat\ A\ UUV}$	Weight of a Category A MUV/UUV [Tonne]
$W_{Cat\ B\ UUV}$	Weight of a Category B UUV [Tonne]
$W_{Cat\ B\&C\ Ind\ LARS}$	Weight of Individual Launch and Recovery System for Category B and C UUVs [Tonne]
$W_{Cat\ B\&C\ LARS}$	Weight of Total Launch and Recovery System(s) for Category B and C UUVs [Tonne]
$W_{Cat\ B\&C\ Payload}$	Weight of Total Category B and C UUVs [Tonne]
$W_{Cat\ B\&C\ Stow}$	Weight of Total Required Stowed for Category B and C [Tonne]
$W_{Cat\ B\&C\ Tube}$	Weight of Launch Tube for Category B and C UUVs [Tonne]
W_{cell}	Weight of a Battery Cell {Tonne]
$W_{CM\ Stow}$	Weight of Stored Countermeasures (Per stowed and launcher bank) [Tonne]
W_{cond}	Weight of Condenser(s) [Tonne]
w_{cond}	Width of Condenser(s) [m]
$W_{Console}$	Weight of a Console [Tonne]
WEO	Weapons Engineering Officer
W_{Furn}	Average Weight of a Piece of Furniture [Tonne]
$W_{Gear\&Clutch}$	Weight of Combined Gearbox and Clutch [Tonne]
$w_{Gear\&Clutch}$	Width of Combined Gearbox and Clutch [m]
$W_{Hand\ Gear}$	Total Weight of Weapon Handling Gear [Tonne]
$W_{Hand\ UUV}$	Weight of Handling Gear for a UUV [Tonne]
W_{Hover}	Hover Tank Weight (Including Flooded Water) [Tonnes]
$W_{HP\ Air}$	Weight of Stored High Pressure Air [Tonne]
W_{HWT}	Weight of Heavyweight Torpedo [Tonne]

W_{IDAS}	Weight of IDAS Missile [Tonne]
W_{Man}	Weight of a Man [Tonne]
W_{MG}	Weight of Motor Generator [Tonne]
W_{Motor}	Weight of Main Electrical Motor [Tonne]
$W_{OP\ Fluids}$	Weight of Operational Fluids for Torpedo Launch System [Tonne]
$W_{Perm\ Ballast}$	Weight of Permanent Ballast [Tonne]
W_{PH}	Total Weight of Pressure Hull(s) [Tonnes]
$W_{PH,\ Plating}$	Weight of Pressure Hull(s) Plating [Tonnes]
W_r	Weight of Each Steam Raising Plant [Tonnes]
W_{rc}	Weight of Each Reactors Compartment [Tonnes]
W_s	Weight of Each Reactors' Shielding [Tonnes]
W_{SE}	Weight of a Signal Ejector [Tonne]
W_{SLMM}	Weight of Submarine Launched Mobile Mine [Tonne]
W_{ST}	Weight of Steam Turbine(s) [Tonne]
w_{ST}	Width of Steam Turbine (s) [m]
W_{Sub}	Weight of Displaced Water (Submerged) [Tonnes]
W_{surf}	Weight of Displaced Water (Surfaced) [Tonnes]
W_{SW}	Weight of Switchboard [Tonne]
w_{SW}	Width of Switchboard [m]
w_T	Taylor Wake Fraction
WTB	Watertight Bulkhead
W_{TG}	Weight of Turbo Generator(s) [Tonne]
w_{TG}	Width of Turbo Generator(s) [m]
W_{TLAM}	Weight of Tomahawk Land Attack Missile [Tonne]
$W_{Torp\ Hand\ Gear}$	Weight of Torpedo Handling Gear [Tonne]
$W_{Torp\ Launch}$	Weight of Torpedo Launch System [Tonne]
$w_{Torp\ Launch}$	Width of Torpedo Launch System [m]
$W_{Torp\ Stow}$	Total Weight of Torpedo (and other Weapons) Stowage Compartment [Tonne]
$W_{Torp\ Tube}$	Weight of Torpedo Tube [Tonne]
$W_{Torp\ Tube\ Bank}$	Weight of Torpedo Tube Bank [Tonne]
$W_{Towed\ Array}$	Weight of Towed Array and Shed [Tonne]
W_{UUV}	Weight of a MUV/UUV [Tonne]
$W_{Weapon\ Payload}$	Total Weight of Weapons Payload [Tonne]
$W_{Weapon\ Storage\ Equip}$	Weight of Weapon Storage Equipment (Excluding Racks) [Tonne]
x_{Batt}	Discharge Margin of Battery Cells
η	Combined efficiency of the propulsor, motor and power electronics. Assumed to be 75%, 95% and 95% respectively, thus an overall efficiency of 67.6% (Goodenough & Greig, 2008)
η_0	Open Water Efficiency of Propeller
η_{CH}	Discharge Efficiency of Batteries
η_{EL}	Efficiency of Motors Converting Electrical Energy to Kinetic Energy
η_H	Hull Efficiency (See Chapter 6 in Burcher & Rydill (1994))
η_R	Rotational Loss Efficiency (of Propulsor, See Chapter 6 in Burcher & Rydill (1994))
η_s	Shaft Transmission Efficiency
θ_{Tail}	Casing Tail-cone Half Angle [Degrees]
ρ	Density [Tonnes/m^3]
ρ_{cell}	Density of Cells [Tonnes/m^3]
ρ_{HY80}	Density of HY80 Steel [Tonnes/m^3]

ρ_{Lead} Density of Lead (For Ballast) [Tonnes/m^3]

F.1 INTRODUCTION

This appendix describes the models and assumptions that comprise part of the Mathematical Modelling Module of SUPERB. The mathematical models for individual equipment items and compartments are described in the first part of this Appendix, followed by the Assumptions Register, which hierarchically codifies the assumptions used in the module.

F.2 TOP LEVEL INPUT VARAIBLES

F.2.1 STRUCTURE INPUT VARIABLES

Assumptions Register Code Number: N/A

F.2.2 PROPULSION INPUT VARIABLES

Assumptions Register Code Number: N/A

F.2.3 PAYLOAD INPUT VARIABLES

Assumptions Register Code Number: 1.3.2

F.2.4 MANNING INPUT VARIABLES

Assumptions Register Code Number[1]: 1.4.1 to 1.4.2

F.3 STRENGTH

F.3.1 PRESSURE HULL(S)

Total Submarine Volume (Submerged) and Volume (Surface):

$$V_{PH}=\frac{W_{sub}}{\rho_{Sea\ Water}} \quad \text{(Eqn. F1)}$$

$$V_{Surf}=V_{PH}/(1+RoB) \quad \text{(Eqn. F2)}$$

Total Weight of Submarine (Surfaced):

$$W_{Surf}=W_{sub}/(1+RoB) \quad \text{(Eqn. F3)}$$

First Estimate of the Diameter for each Pressure Hull:

$$D_{PH}=0.7\left(\frac{V_{PH}}{Num_{PH}}\right)^{0.3} \quad \text{(Eqn. F4)}$$

Second Estimate of the Diameter of each Pressure Hull. Assumptions Register Code Number: 2.1.2

[1] For each code number, it includes every assumption that is a ‘child’ of the given code number.

$$D_{PH}=\left\lfloor\left|\overline{D_{PH,\ Aretzen}}-D_{PH}+0.5\ H_{PH}\right|\right\rfloor \qquad \text{(Eqn. F5)}$$

Length of Cylinder Section of each Pressure Hull. Assumptions Register Code Number: 2.1.5

$$L_{cyl}=\frac{\left(\left(\frac{V_{PH}}{Num_{PH}}\right)-0.08\ \pi\ D_{PH}{}^{3}\right)}{0.25\pi D_{PH}{}^{2}} \qquad \text{(Eqn. F6)}$$

Total Length of each Pressure Hull. Assumptions Register Code Number: 2.1.5

$$L_{PH}=L_{cyl}+\frac{2}{3.5}D_{PH} \qquad \text{(Eqn. F7)}$$

Wall Thickness for each Pressure Hull Plating (HY80 Steel). Assumptions Register Code Number: 2.1.1

$$te_{PH\ HY80}=0.14D_{PH}(FOS_{PH}DDD^{0.7}) \qquad \text{(Eqn. F8)}$$

Weight of Pressure Hull(s) Plating:

$$W_{PH,\ \ Plating}=Num_{PH}\rho_{HY80}\left(\pi\ D_{PH}\ L_{cyl}\left(\frac{te_{PH\ HY80}}{1000}\right)+2\ \pi\left(\frac{D_{PH}}{2}\right)^{2}\left(\frac{te_{PH\ HY80}}{1000}\right)\right) \qquad \text{(Eqn. F9)}$$

Total Weight of Pressure Hulls (Plating and Stiffeners):

$$W_{PH}=1.4\ W_{PH,\ \ Plating} \qquad \text{(Eqn. F10)}$$

Deck Height (Habitable Decks). Assumptions Register Code Number: 2.1.4

$$DH=H_{PH}-H_{Unavailable} \qquad \text{(Eqn. F11)}$$

Tankage Deck Height:

$$R=D_{PH}-Num_{Decks}H_{PH} \qquad \text{(Eqn. F12)}$$

F.3.2 CASING

Average Diameter of Casing Assumptions Register Code Number: 2.2.7

$$D_{ave}=\begin{cases}(2D_{so}+D_{PH}),\ \ \text{Single PH}\\ \frac{(2D_{so}+2D_{PH}+PH_{Gap})+(2D_{so}+D_{PH})}{2}.\ \ \text{Twin PHs}\end{cases} \qquad \text{(Eqn. F13)}$$

The Free Flood Volume for Cylinder Section. Assumptions Register Code Number: 2.2.11

$$V_{bh}=\begin{cases}0.25L_{cyl}\ \ \pi\ D_{ave}{}^{2}-0.25Num_{PH}\ \pi\ L_{cyl}\ D_{PH}{}^{2})\\ +0.08\ Num_{PH}\ \pi\ D_{PH}{}^{3},\ \ \text{Double Hull (i.e. } D_{so}=/=0)\\ 0,\ \ \ \text{Single Hull (i.e. } D_{so}=0)\end{cases} \qquad \text{(Eqn. F14)}$$

Length of Forward End and Aft End of Casing. Assumptions Register Code Number: 2.2.6

$$L_{fe}=Casing_{End\ Ratio}D_{PH} \qquad \text{(Eqn. F15a)}$$

$$L_{ae}=Casing_{End\ Ratio}D_{PH} \qquad \text{(Eqn. F15b)}$$

Volume of Forward End of Casing. Assumptions Register Code Number: 2.2.11

$$V_{fe}=\begin{cases}\frac{2}{3}\pi\left(\frac{D_{ave}}{2}\right)^2 L_{fe}\text{-}0.04\pi\ D_{PH}{}^3\text{, Single PH}\\ \frac{2}{3}\pi\left(\frac{D_{ave}}{2}\right)^2 L_{fe}\text{- }Num_{PH}0.04\pi\ D_{PH}{}^3\text{, Twin PHs}\end{cases}\qquad\text{(Eqn. F16)}$$

Volume of Aft End of Casing. Assumptions Register Code Number: 2.2.11

$$V_{ae}=\begin{cases}\frac{21}{50}\pi\left(\frac{D_{ave}}{2}\right)^2 L_{fe}\text{-}0.04\pi\ D_{PH}{}^3\text{,Single PH}\\ \frac{21}{50}\pi\left(\frac{D_{ave}}{2}\right)^2 L_{fe}\text{- }Num_{PH}0.04\pi\ D_{PH}{}^3\text{,Twin PHs,}\end{cases}\qquad\text{(Eqn. F17)}$$

Volume of Casing above Pressure Hull (Not Including the Bridge Fin). Assumptions Register Code Number: 2.2.8 to 2.2.10

$$V_{Top}=\begin{cases}L_{cyl}D_{PH}H_{Top},\ \text{Single Hull (i.e. }D_{so}\text{=0)}\\ 0,\ \text{Double Hull (i.e. }D_{so}\text{=/=0) (N.B. different from Twin Hull)}\end{cases}\qquad\text{(Eqn. F18)}$$

Total Length of Casing. Assumptions Register Code Number: 2.2.11

$$LOA=L_{fe}+L_{cyl}+L_{ae}\qquad\text{(Eqn. F19)}$$

Floodable Volume of Casing (Less the Bridge Fin). Assumptions Register Code Number: 2.2.12

$$V_k=V_{fe}+V_{bh}+V_{ae}+V_{Top}\qquad\text{(Eqn. F20)}$$

Volume of Bridge Fin. Assumptions Register Code Number: 2.2.1 and 2.2.5

$$V_{Fin}=BC_{Fin}w_{Fin}\ L_{Fin}\ H_{Fin}\qquad\text{(Eqn. F21)}$$

Total Volume of Casing. Assumptions Register Code Number: 2.2.12

$$V_{Form}=V_k+V_{Fin}+V_{PH}\qquad\text{(Eqn. F22)}$$

Total Weight of Casing. Assumptions Register Code Number: 2.2.13

$$W_{cas}=0.015\left(\frac{2}{3}\right)\pi\ D_{ave}\ L_{cyl}\ \rho_{HY80}\qquad\text{(Eqn. F23)}$$

F.3.3 HYDROPLANES AND RUDDERS

Assumptions Register Code Number: 2.2.14 to 2.2.25

F.3.4 MAIN BALLAST TANKS (MBTs)

Required Flooded Volume of MBTs:

$$V_{mbte}=\frac{(W_{sub}\text{-}W_{surf})}{\rho_{Sea\ Water}}\qquad\text{(Eqn. F24)}$$

Required Total Volume of MBTs. Assumptions Register Code Number: 2.3.1

$$V_{mbte,\ req}=\frac{V_{mbte}}{K_{mbte}}\qquad\text{(Eqn. F25)}$$

Un-flooded Volume of MBTs. Assumptions Register Code Number: 2.2.12

$$V_{mbte,\ spare}=V_{mbte,\ req}\text{-}V_{mbte}\qquad\text{(Eqn. F26)}$$

F.3.5 HOVER, COMPENSATION AND TRIM TANKS

Combined Ratio of Displaced (Surfaced) Volume used for Trim and Compensation.

$$Ratio_{Trim\&Comp}=Ratio_{Trim}+Ratio_{Comp} \qquad \text{(Eqn. F27)}$$

Useable Trim and Compensation Tanks Volume. Assumptions Register Code Number: 2.4.1

$$V'_{Trim\&Comp}=Ratio_{Trim\&Comp}V_{surf} \qquad \text{(Eqn. F28)}$$

Required Trim and Compensation Tanks Volume. Assumptions Register Code Number: 2.4.1

$$V_{Trim\&Comp}=\frac{V'_{Trim\&Comp}}{K_{Trim\&Comp}{}^{2}} \qquad \text{(Eqn. F29)}$$

Useable Trim Tanks Volume. Assumptions Register Code Number: 2.4.2

$$V'_{Trim}=Ratio_{Trim}V_{surf} \qquad \text{(Eqn. F30)}$$

Required Trim Tanks Volume. Assumptions Register Code Number: 2.4.1

$$V_{Trim}=\frac{V'_{Trim}}{K_{Trim\&Comp}{}^{2}} \qquad \text{(Eqn. F31)}$$

Useable Compensation Tank Volume. Assumptions Register Code Number: 2.4.3

$$V'_{Comp}=Ratio_{Comp}V_{surf} \qquad \text{(Eqn. F32)}$$

Required Compensation Tank Volume. Assumptions Register Code Number: 2.4.1

$$V_{Comp}=\frac{V'_{Comp}}{K_{Trim\&Comp}{}^{2}} \qquad \text{(Eqn. F33)}$$

Hover Tank Volume. Assumptions Register Code Number: 2.4.4

$$V_{Hover}=0.025\ V_{PH} \qquad \text{(Eqn. F34)}$$

Hover Tank Weight (including Flooded Water). Assumptions Register Code Number: 2.4.5

$$W_{Hover}=1.05\ V_{Hover}\rho_{Sea\ Water} \qquad \text{(Eqn. F35)}$$

F.3.6 ESCAPE TOWERS

Assumptions Register Code Number: 2.5.1 to 2.5.4

F.3.7 CONNING TOWER

Assumptions Register Code Number: 2.6.1 to 2.6.4

F.3.8 BILGE WATER TANK

Assumptions Register Code Number: 2.7.1 and 2.7.2

F.3.9 MISCELLANEOUS FITTINGS

Assumptions Register Code Number: 2.8

F.4 PROPULSION

F.4.1 PROPELLER

Aspect Ratio (Length to Diameter) of Casing:

$$\mathrm{Ratio}_{L:D}=\frac{\mathrm{LOA}}{D_{ave}} \quad \text{(Eqn. F36)}$$

Angle of Tail Section of Casing:

$$\theta_{Tail}=\tan^{-1}\left(\frac{D_{Ave}}{2\ L_{ae}}\right) \quad \text{(Eqn. F37)}$$

Thrust Deduction from Hull Resistance. Assumptions Register Code Number: 3.1.5

$$t=0.24-0.02\left(\frac{\mathrm{Ratio}_{D_{Prop}:D}-0.4}{0.1}\right)+0.05\left(\frac{\theta_{Tail}-60}{10}\right) \quad \text{(Eqn. F38)}$$

Taylor Wake Fraction. Assumptions Register Code Number: 3.1.5

$$w_t=0.48-0.03\left(\frac{\mathrm{Ratio}_{D_{Prop}:D}-0.4}{0.1}\right)+0.04\left(\frac{\theta_{Tail}-60}{10}\right) \quad \text{(Eqn. F39)}$$

Hull Efficiency for Propulsion. Assumptions Register Code Number: 3.1.5

$$\eta_H=\begin{cases}\text{Single PH,} & \dfrac{1-t}{1-w_t}\\ \text{Twin PHs,} & \dfrac{1-t}{1-w_t}-0.4\end{cases} \quad \text{(Eqn. F40)}$$

Propulsive Efficiency Coefficient. Assumptions Register Code Number: 3.1.1 to 3.1.3

$$PC=\eta_H\ \eta_o\ \eta_R\eta_s \quad \text{(Eqn. F41)}$$

Hydrodynamic Hull Form Coefficient. Assumptions Register Code Number: 3.1.6

$$Kp=20+|\mathrm{Ratio}_{L:D}-6|^{1.2} \quad \text{(Eqn. F42)}$$

Effective Propulsive Shaft Power for Maximum Velocity. Assumptions Register Code Number: 3.1.6

$$P_{shaft\ eff.\ max}=\frac{Kp\ V_{Form}^{0.64}(0.51444\ U_{Max})^{2.9}}{10^6} \quad \text{(Eqn. F43)}$$

Required Propulsive Shaft Power for Maximum Velocity:

$$P_{shaft\ req.\ max}=\frac{P_{shaft\ effmax}}{PC} \quad \text{(Eqn. F44)}$$

Maximum Speed (after the Engine/Reactor is selected). Assumptions Register Code Number: 3.1.6

$$U_{Max}=\frac{1}{0.51444}\left(\frac{10^6\ P_{shaft\ eff.\ max}}{Kp\ V_{Form}^{0.64}}\right)^{1/2.9} \quad \text{(Eqn. F45)}$$

F.4.2 NUCLEAR POWER

Required Power from Turbo Generator(s) for Non-Propulsive Loads. Assumptions Register Code Number: 3.2.5

$$P_{TG'}=\frac{3}{7}P_{shaft\ req.\ max} \quad \text{(Eqn. F46)}$$

Required Total Power of Reactor(s):

$$P_{Req}=P_{TG'}+P_{shaft\ req.\ max} \quad \text{(Eqn. F47)}$$

Required Thermal Total Power of Each Reactor. Assumptions Register Code Number: 3.2.1

$$P_{Ther}=\frac{P_{Req}}{0.3Num_{Reactors}} \quad \text{(Eqn. F48)}$$

Weight of Each Nuclear Steam Raising Plant. Assumptions Register Code Number: 3.2.1

$$W_r=41.365\ P_{Ther}^{0.5} \quad \text{(Eqn. F49)}$$

Volume of Each Reactor Compartment. Assumptions Register Code Number: 3.2.6

$$V_{rc}=41.952\ P_{Ther}^{0.609} \quad \text{(Eqn. F50)}$$

Length of Each Reactor Compartment. Assumptions Register Code Number: 3.2.7

$$L_{rc}=3.43\ P_{Ther}^{0.19} \quad \text{(Eqn. F51)}$$

Diameter of Each Reactor Compartment. Assumptions Register Code Number: 3.2.7

$$D_{rc}=5.96\ P_{Ther}^{0.114} \quad \text{(Eqn. F52)}$$

Weight of Each Reactor’s Shielding. Assumptions Register Code Number: 3.2.8

$$W_s=0.125\pi D_{rc}^2+0.5\ V_{rc} \quad \text{(Eqn. F53)}$$

Weight of Each Reactor Compartment:

$$W_{rc}=W_r+W_s \quad \text{(Eqn. F54)}$$

Thermal Power in Secondary Circuit of Each Reactor. Assumptions Register Code Number: 3.2.4

$$P_{2nd}=0.9\ P_{Ther} \quad \text{(Eqn. F55)}$$

Total Flow Rate in Secondary Circuit of Each Reactor. Assumptions Register Code Number: 3.2.9

$$F'=\frac{P_{2nd}}{0.429} \quad \text{(Eqn. F56)}$$

Total Flow Rate to Steam Turbine(s). Assumptions Register Code Number: 3.2.2

$$F'_{ST}=0.7\ Num_{Reactors}F' \qquad \text{(Eqn. F57)}$$

Total Flow Rate to Turbo Generator(s). Assumptions Register Code Number: 3.2.3

$$F'_{TG}=0.3\ Num_{Reactors}F' \qquad \text{(Eqn. F58)}$$

Power of Steam Turbine(s). Assumptions Register Code Number: 3.2.2

$$P_{ST}=0.16\ F'_{ST} \qquad \text{(Eqn. F59)}$$

Power of Turbo Generator(s). Assumptions Register Code Number: 3.2.3

$$P_{TG}=0.09\ F'_{TG} \qquad \text{(Eqn. F60)}$$

Minimum Volume of Machinery Compartment(s). Assumptions Register Code Number: 3.2.10

$$V_{mc}=160\text{-}F'^{0.417} \qquad \text{(Eqn. F61)}$$

F.4.3 BATTERY POWER

Maximum Time Allowable on Batteries. Assumptions Register Code Number: 3.3.5

$$T_{Batt}=\frac{Esc_{Dist}}{U_{esc}} \qquad \text{(Eqn. F62)}$$

Effective Propulsive Power at Emergency Escape Velocity:

$$P_{shaft\ eff.\ esc}=\frac{Kp\ V_{Form}{}^{0.64}(0.51444\ U_{esc})^{2.9}}{10^6} \qquad \text{(Eqn. F63)}$$

Required Propulsive Power at Emergency Escape Velocity:

$$P_{shaft\ req.\ esc}=\frac{P_{shaft\ eff.\ esc}}{PC\ \eta_{EL}} \qquad \text{(Eqn. F64)}$$

Energy Stored in each Cell. Assumptions Register Code Number: 3.3.6 to 3.3.8

$$E_{Cell}=(0.001\ K_{Batt}\ \left(\frac{T_{Batt}}{(1\text{-}x_{Batt})}\right)^{n_{Batt}} \qquad \text{(Eqn. F65)}$$

Energy Discharged in each Cell. Assumptions Register Code Number: 3.3.2

$$E_{Dis}=\eta_{CH}E_{Cell} \qquad \text{(Eqn. F66)}$$

Charging Time for each Cell for Emergency Escape. Assumptions Register Code Number: 3.3.3 and 3.3.14

$$T_{CH\ Esc}=\frac{\left(1000000\ E_{Dis}\text{-}\left(1.225\ (I_{max}+I_{max})\right)\right)}{2.25\ I_{max}} \qquad \text{(Eqn. F67)}$$

Hotel Power. Assumptions Register Code Number: 3.3.1

$$P_{Hotel}=\frac{W_{sub}}{10000} \quad \text{(Eqn. F68)}$$

Total Required Power to be Provided by Batteries. Assumptions Register Code Number: 3.3.16

$$P_{req.\ Batt}=P_{Hotel}+\frac{P_{shaft\ req.\ esc}}{\eta_{EL}} \quad \text{(Eqn. F69)}$$

Required Total Energy Stored of Cells. Assumptions Register Code Number: 3.3.6

$$E_{Esc}=P_{req.\ Batt}\frac{T_{Batt}}{1-x_{Batt}} \quad \text{(Eqn. F70)}$$

Required Number of Cells:

$$Num_c=\left\lceil\frac{E_{Esc}}{E_{Dis\ Esc}}\right\rceil \quad \text{(Eqn. F71)}$$

Total Weight of Cells. Assumptions Register Code Number: 3.3.9

$$W_{Batt}=Num_c W_{cell} \quad \text{(Eqn. F72)}$$

Total Volume of Cells. Assumptions Register Code Number: 3.3.10

$$V_{Batt}=W_{Batt}/\rho_{cell} \quad \text{(Eqn. F73)}$$

Mean Power to Recharge Cells:

$$P_{CH\ Esc}=\frac{E_{Esc}}{T_{CH\ Esc}} \quad \text{(Eqn. F74)}$$

Maximum Time Submerged for Emergency Escape. Assumptions Register Code Number: 3.3.15

$$T_{sub\ Esc}=(1-x_{Batt})\left(\frac{K_{Batt}Num_c}{1000\ P_{req.\ Batt}}\right)^{1/(1-n_{Batt})} \quad \text{(Eqn. F75)}$$

Indiscretion Ratio during Emergency Escape:

$$IR_{esc}=\frac{T_{CH\ Esc}}{T_{CH\ Esc}+T_{sub\ Esc}} \quad \text{(Eqn. F76)}$$

F.4.4 NON-NUCLEAR POWER

Time to Transit to Nearest Friendly Port on Non-Nuclear Propulsion. Assumptions Register Code Number: 3.4.2.16

$$T'_{Trans}=\frac{2000}{24\ U'_{Trans}} \quad \text{(Eqn. F77)}$$

Total Non-Nuclear Power:

$$P_{Non\ Nuke}=Num_{Non\ Nuke\ Engine}P_{Non\ Nuke\ Engine} \quad \text{(Eqn. F78)}$$

Non-Nuclear Propulsion Transit Speed Power:

$$P_{Non\ Nuke\ Trans}=\frac{Kp\ V_{Form}{}^{0.64}(0.51444\ U'_{Trans})^{2.9}}{10^6} \quad \text{(Eqn. F79)}$$

Maximum Time Submerged for Non-Nuclear Propulsion Sprint:

$$T'_{sub\ Sprint}=(1-x_{Batt})\left(\frac{K_{Batt}Num_c}{1000\ P_{Non\ Nuke}}\right)^{1/(1-n_{Batt})} \quad \text{(Eqn. F80)}$$

Maximum Time Submerged for Non-Nuclear Propulsion Transit:

$$T'_{sub\ Trans}=(1-x_{Batt})\left(\frac{K_{Batt}Num_c}{1000\ P_{Non\ Nuke\ Trans}}\right)^{1/(1-n_{Batt})} \quad \text{(Eqn. F81)}$$

Charging Time for each Cell during Non-Nuclear Propulsion Sprint. Assumptions Register Code Number: 3.4.4.26 and 3.4.3.8

$$T'_{CH\ Sprint}=\begin{cases}\dfrac{\left(1000000\ E_{Dis}-\left(1.225\ (I_{max}+I_{max})\right)\right)}{2.25\ I_{max}}, & \text{Diesel}\\ 0, & \text{Stirling Engine or Fuel Cell or CCST}\end{cases} \quad \text{(Eqn. F82)}$$

Charging Time for each Cell during Non-Nuclear Propulsion Transit. Assumptions Register Code Number: 3.4.4.26 and 3.4.3.8

$$T'_{CH\ Trans}=\begin{cases}\dfrac{\left(1000000\ E_{Dis}-\left(1.225\ (I_{max}+I_{max})\right)\right)}{2.25\ I_{max}}, & \text{Diesel}\\ 0, & \text{Stirling Engine or Fuel Cell or CCST}\end{cases} \quad \text{(Eqn. F83)}$$

Indiscretion Ratio during Non-Nuclear Propulsion Sprint:

$$IR'_{Sprint}=\frac{T'_{CH\ Sprint}}{T'_{CH\ Sprint}+T'_{sub\ Sprint}} \quad \text{(Eqn. F84)}$$

Indiscretion Ratio during Non-Nuclear Propulsion Transit:

$$IR'_{Trans}=\frac{T'_{CH\ Trans}}{T'_{CH\ Trans}+T'_{sub\ Trans}} \quad \text{(Eqn. F85)}$$

Average Effective Sprint Power on Non-Nuclear Propulsion. Assumptions Register Code Number: 3.3.16

$$P'_{sprint}=\eta_{EL}PC\left(P_{Non\ Nuke}-P_{Hotel}-IR'_{sprint}P'_{CH\ Sprint}\right) \quad \text{(Eqn. F86)}$$

Average Effective Transit Power on Non-Nuclear Propulsion. Assumptions Register Code Number: 3.3.16

$$P'_{Trans}=\eta_{EL}PC(P_{Non\ Nuke}-P_{Hotel}-IR'_{Trans}P'_{CH\ Trans}) \qquad \text{(Eqn. F87)}$$

Energy (i.e. Fuel) to be Stored. Assumptions Register Code Number: 3.3.16

$$E_{Fuel}=(T'_{Trans}+T_{on\text{-}station})\left(\frac{P'_{Trans}}{PC\eta_{EL}}+P_{Hotel}+IR'_{Trans}P'_{CH\ Trans}\right) \qquad \text{(Eqn. F88)}$$

F.4.5 PROPULSION EQUIPMENT

Main Electrical Motor Diameter. Assumptions Register Code Number: 3.5.6.2

$$D_{Motor}=0.14\ \frac{1000P'_{sprint}}{500} \qquad \text{(Eqn. F89)}$$

Main Electrical Motor Length Assumptions Register Code Number: 3.5.6.2

$$L_{Motor}=1.5\ D_{Motor} \qquad \text{(Eqn. F90)}$$

Main Electrical Motor Weight. Assumptions Register Code Number: 3.5.6.3

$$W_{Motor}=2.6\ D_{Motor}{}^{3} \qquad \text{(Eqn. F91)}$$

Motor Generator Diameter. Assumptions Register Code Number: 3.5.8.2

$$D_{MG}=\begin{cases}0.2\dfrac{(P_{Hotel}+IR'_{Trans}P'_{CH\ Trans})}{0.07\ Num_{MG}}+0.6, & \text{CCST, Stirling Engine or Diesel}\\ 0, & \text{Fuel Cell}\end{cases} \qquad \text{(Eqn. F92)}$$

Motor Generator Length. Assumptions Register Code Number: 3.5.8.2

$$L_{MG}=\begin{cases}0.6\dfrac{(P_{Hotel}+IR'_{Trans}P'_{CH\ Trans})}{0.07\ Num_{MG}}+1.2, & \text{CCST, Stirling Engine or Diesel}\\ 0, & \text{Fuel Cell}\end{cases} \qquad \text{(Eqn. F93)}$$

Motor Generator Weight. Assumptions Register Code Number: 3.5.8.2

$$W_{MG}=\begin{cases}2\dfrac{(P_{Hotel}+IR'_{Trans}P'_{CH\ Trans})}{0.07\ Num_{MG}}+2, & \text{CCST, Stirling Engine or Diesel}\\ 0, & \text{Fuel Cell}\end{cases} \qquad \text{(Eqn. F94)}$$

Switchboard Length. Assumptions Register Code Number: 3.5.2.1

$$L_{Sw}=\frac{1}{0.25^{\frac{1}{3}}}P_{shaft\ req.\ max}{}^{\frac{1}{3}} \qquad \text{(Eqn. F95)}$$

Switchboard Width. Assumptions Register Code Number: 3.5.2.1

$$w_{Sw}=0.25^{\frac{2}{3}}P_{shaft\ req.\ \ max}{}^{\frac{1}{3}}+1$$ (Eqn. F96)

Switchboard Volume. Assumptions Register Code Number: 3.5.2.1

$$V_{Sw}=P_{shaft\ req.\ \ max}{}^{\frac{1}{3}}+0.7P_{Non\ Nuke}+0.01Num_c$$ (Eqn. F97)

Switchboard Weight. Assumptions Register Code Number: 3.5.2.2

$$W_{Sw}=1.0\ P_{Non\ Nuke}$$ (Eqn. F98)

Gearbox and Clutch Weight. Assumptions Register Code Number: 3.5.7.2

$$W_{Gear\&Clutch}=\frac{1000P_{shaft\ req.\ \ max}}{348750}$$ (Eqn. F99)

Gearbox and Clutch Width. Assumptions Register Code Number: 3.5.7.1

$$w_{Gear\&Clutch}=2\left(\frac{1000P_{shaft\ req.\ \ max}}{11250}\right)^{0.5}$$ (Eqn. F100)

Gearbox and Clutch Height. Assumptions Register Code Number: 3.5.7.1

$$H_{Gear\&Clutch}=1.54\left(\frac{1000P_{shaft\ req.\ \ max}}{11250}\right)^{0.5}$$ (Eqn. F101)

Weight of Condenser(s). Assumptions Register Code Number: 3.5.1.3

$$W_{cond}=0.28\frac{2.33}{Num_{cond}}P_{Ther}$$ (Eqn. F102)

Length of Condenser(s). Assumptions Register Code Number: 3.5.1.1

$$L_{cond}=3.6\left(\frac{3.7\ W_{cond}}{25\ DH}\right)$$ (Eqn. F103)

Width of Condenser(s). Assumptions Register Code Number: 3.5.1.1

$$w_{cond}=1.05\left(\frac{3.7\ W_{cond}}{25\ DH}\right)$$ (Eqn. F104)

Number of Turbo Generators(s). Assumptions Register Code Number: 3.5.4.1

$$Num_{TG}=\max\left(\left\lceil Dph-\left(1.7985\ \left(\frac{Ptg}{Num_{TG}}\right)-0.9738\right)\right\rceil,2\right)$$ (Eqn. F105)

Weight of Turbo Generator(s). Assumptions Register Code Number: 3.5.4.3

$$W_{TG}=4.6316\ \frac{P_{TG}}{Num_{TG}}+10.111$$ (Eqn. F106)

Length of Turbo Generator(s). Assumptions Register Code Number: 3.5.4.2

$$L_{TG}=1.7755\frac{P_{TG}}{Num_{TG}}-0.7615 \quad \text{(Eqn. F107)}$$

Width of Turbo Generator(s). Assumptions Register Code Number: 3.5.4.2

$$w_{TG}=1.0827\frac{P_{TG}}{Num_{TG}}-0.0391 \quad \text{(Eqn. F108)}$$

Height of Turbo Generator(s). Assumptions Register Code Number: 3.5.4.2

$$H_{TG}=1.7985\frac{P_{TG}}{Num_{TG}}-0.9738 \quad \text{(Eqn. F109)}$$

Weight of Steam Turbine(s). Assumptions Register Code Number: 3.5.5.1

$$W_{ST}=2.25\frac{P_{ST}}{Num_{ST}}+10.111 \quad \text{(Eqn. F110)}$$

Volume of Steam Turbine(s). Assumptions Register Code Number: 3.5.5.2

$$V_{ST}=4.86\,W_{ST} \quad \text{(Eqn. F111)}$$

Length of Steam Turbine(s). Assumptions Register Code Number: 3.5.5.2

$$L_{ST}=\left(\frac{V_{ST}}{\frac{\pi}{16}}\right)^{1/3} \quad \text{(Eqn. F112)}$$

Width of Steam Turbine(s). Assumptions Register Code Number: 3.5.5.2

$$w_{ST}=0.5\,L_{ST} \quad \text{(Eqn. F113)}$$

F.5 AUXILIARY MACHINERY

Total Weight of Stored High Pressure Air. Assumptions Register Code Number: 3.6.1.1 and 3.6.1.2

$$W_{HP\ Air}=\frac{0.4V_{PH}}{1000} \quad \text{(Eqn. F114)}$$

High Pressure Air Compressor Capacity. Assumptions Register Code Number: 3.6.1.1

$$Comp_{HP\ Air}=500\,W_{HP\ Air} \quad \text{(Eqn. F115)}$$

Required Cooling Power of Chilled Water Plant. Assumptions Register Code Number: 3.6.2.2

$$P_{CWP}=0.000075(Num_{TG}V_{TG}+Num_{ST}V_{ST}+Num_{Motor}V_{Motor}+Num_{Cond}V_{Cond}) \quad \text{(Eqn. F116)}$$

F.6 PAYLOAD

F.6.1 UUV

Volume of a UUV/MUV:

$$V_{UUV}=\frac{W_{UUV}}{\rho_{Sea\ Water}} \qquad \text{(Eqn. F117)}$$

Diameter of a Body of Revolution UUV/MUV. Assumptions Register Code Number: 4.1.1.3

$$D_{UUV}=\left(\frac{0.8\ W_{UUV}}{\pi}\right)^{0.5} \qquad \text{(Eqn. F118)}$$

Length of a Body of Revolution UUV/MUV. Assumptions Register Code Number: 4.1.1.3

$$L_{UUV}=8\ D_{UUV} \qquad \text{(Eqn. F119)}$$

Volume Required to Store a Body of Revolution UUV/MUV. Assumptions Register Code Number: 4.1.1.20

Category A UUV/MUV Launch Tube Wall Thickness. Assumptions Register Code Number: 4.1.1.6

$$V_{Store\ UUV}=1.5\ L_{UUV}\ D_{UUV}^{\ 2} \qquad \text{(Eqn. F120)}$$

and 4.1.1.7

$$te_{Cat\ A\ HY80}=0.14D_{Cat\ A\ UUV}(DDD^{0.7}) \qquad \text{(Eqn. F121)}$$

Category A UUV/MUV Launch Tube Weight. Assumptions Register Code Number: 4.1.1.7

$$W_{Cat\ A\ Tube}=\pi\ te_{Cat\ A\ HY80}\ D_{Cat\ A\ UUV}\ L_{Cat\ A\ UUV}\ \rho_{HY80} \qquad \text{(Eqn. F122)}$$

Category A UUV/MUV Launch Tube Volume. Assumptions Register Code Number: 4.1.1.7

$$V_{Cat\ A\ Tube}=\frac{\pi}{4}D_{Cat\ A\ UUV}^{\ 2}\ L_{Cat\ A\ UUV} \qquad \text{(Eqn. F123)}$$

Category B (and C) UUV Launch Tube Volume. Assumptions Register Code Number: 4.1.2.4

$$V_{Cat\ B\&C\ Tube}=\frac{V_{UUV\ Cat\ B}}{V_{HWT}}V_{21"\ Tube} \qquad \text{(Eqn. F124)}$$

Handling Equipment Weight for each UUV/MUV. Assumptions Register Code Number: 4.1.1.14

$$W_{Hand\ UUV}=0.2\ W_{UUV} \qquad \text{(Eqn. F125)}$$

Category A UUV/MUV Individual LARS Weight. Assumptions Register Code Number: 4.1.1.4

$$W_{Cat\ A\ Ind\ LARS}=0.5\ W_{Cat\ A\ UUV} \qquad \text{(Eqn. F126)}$$

Category B (and C) UUV Individual LARS Weight. Assumptions Register Code Number: 4.1.2.3 and 4.1.2.10

$$W_{Cat\ B\&C\ Ind\ LARS}=\frac{W_{UUV\ Cat\ B}}{W_{HWT}}W_{21"\ Tube\ Equip} \quad \text{(Eqn. F127)}$$

Category A UUV/MUV Total LARS Compartment Weight (Self Contained LARS). Assumptions Register Code Number: 4.1.2.3 and 4.1.2.10

$$W_{Cat\ A\ LARS}=\begin{cases} Num_{Cat\ A}(W_{Cat\ A\ Ind\ LARS}+W_{Hand\ Cat\ A}+W_{Cat\ A\ Tube}+\rho_{Sea\ Water}V_{Cat\ A\ Tube}), \&Flooded \\ Num_{Cat\ A}(W_{Cat\ A\ LARS}+W_{Hand\ Cat\ A}+W_{Cat\ A\ Tube}), \&Unflooded \end{cases} \quad \text{(Eqn. F128)}$$

Category A UUV/MUV Total LARS Compartment Weight (Single Interface LARS). Assumptions Register Code Number: 4.1.1.6

$$W_{Cat\ A\ LARS}=\begin{cases} Num_{Cat\ A}(W_{Cat\ A\ Ind\ LARS}+W_{Hand\ Cat\ A})+W_{Cat\ A\ Tube}+\rho_{Sea\ Water}V_{Cat\ A\ Tube}, \&Flooded \\ Num_{Cat\ A}(W_{Cat\ A\ LARS}+W_{Hand\ Cat\ A})+W_{Cat\ A\ Tube}, \&Unflooded \end{cases} \quad \text{(Eqn. F129)}$$

Category B and C UUV Total LARS Compartment Weight. Assumptions Register Code Number: 4.1.1.5

$$W_{Cat\ B\&C\ LARS}=\begin{cases} \left\lceil\frac{(Num_{Cat\ B}+Num_{Cat\ C})}{6}\right\rceil(W_{Cat\ B\ Ind\ LARS}+W_{Cat\ B\&C\ Tube} \\ \quad +\rho_{Sea\ Water}V_{Cat\ B\ Tube}), \&Flooded \\ \left\lceil\frac{(Num_{Cat\ B}+Num_{Cat\ C})}{6}\right\rceil(W_{Cat\ B\&C\ LARS}+W_{Cat\ B\&C\ Tube}),Unflooded \end{cases} \quad \text{(Eqn. F130)}$$

Category A MUV/UUV Total LARS Compartment Volume. Assumptions Register Code Number: 4.1.2.6

$$V_{Cat\ A\ LARS}=\begin{cases} Num_{Cat\ A}(V_{Cat\ A\ LARS}+V_{Cat\ A\ Tube}),Self\ Contained\ LARS \\ (V_{Cat\ A\ LARS}+V_{Cat\ A\ Tube}),Single\ Interface\ LARS \end{cases} \quad \text{(Eqn. F131)}$$

F.6.2 ELECTRONIC PAYLOAD

Number of CPUs Required for Masts:

$$Num_{CPU,\ Masts}=Num_{Comm\ \ Masts}+Num_{Optronic\ \ Masts}+Num_{Radar\ \ Masts} \quad \text{(Eqn. F132)}$$
$$+Num_{Exh\ \ Masts}+Num_{Int\ \ Masts}+Num_{Triple\ M}$$

Number of Consoles Required for Masts:

$$Num_{Console,\ Masts}=Num_{Comm\ \ Masts}+Num_{Optronic\ \ Masts}+Num_{Radar\ \ Masts}+ \quad \text{(Eqn. F133)}$$
$$Num_{Exh\ \ Masts}+Num_{Int\ \ Masts}+Num_{Triple\ M}$$

Length of Flank Array. Assumptions Register Code Number: 4.2.2.1

$$L_{\text{Flank Array}}=\left\lceil\frac{LOA}{5}\right\rceil \quad \text{(Eqn. F134)}$$

Weight of Towed Array (Including Shed). Assumptions Register Code Number: 4.2.3.2 and 4.2.3.1

$$W_{\text{Towed Array}}=\begin{cases} 1.8+0.015L_{\text{Towed Array}}, & \text{Towed Array in Drum} \\ 0.6+0.015L_{\text{Towed Array}}, & \text{Retractable Towed Array} \end{cases} \quad \text{(Eqn. F135)}$$

F.6.3 COMMAND COMPARTMENTS

Volume of C2 Room. Assumptions Register Code Number: 4.3.1

$$V_{\text{C2 Rm}}=\max\left(V_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, C2 Rm}}}{5}\right\rceil+V_{\text{Console}}Num_{\text{Console, C2 Rm}}+6,10\right) \quad \text{(Eqn. F136)}$$

Weight of C2 Room. Assumptions Register Code Number: 4.3.1

$$W_{\text{C2 Rm}}=W_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, C2 Rm}}}{5}\right\rceil+W_{\text{Console}}Num_{\text{Console, C2 Rm}} \quad \text{(Eqn. F137)}$$

$$+Num_{\text{Complement, C2 Rm}}(W_{\text{man}}+W_{\text{Furn}})+1$$

Volume of Communications Room. Assumptions Register Code Number: 4.3.3

$$V_{\text{Comm Rm}}=\max\left(V_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, Comm Rm}}}{5}\right\rceil+V_{\text{Console}}Num_{\text{Console, Comm Rm}}+15,10\right) \quad \text{(Eqn. F138)}$$

Weight of Communications Room. Assumptions Register Code Number: 4.3.3

$$W_{\text{Comm Rm}}=W_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, Comm Rm}}}{5}\right\rceil \quad \text{(Eqn. F139)}$$

$$+W_{\text{Console}}Num_{\text{Console, Comm Rm}}+Num_{\text{Complement, Comm Rm}}(W_{\text{man}}+W_{\text{Furn}})+1$$

Volume of MCC Room. Assumptions Register Code Number: 4.3.2

$$V_{\text{MCC Rm}}=\max\left(V_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, MCC Rm}}}{5}\right\rceil+V_{\text{Console}}Num_{\text{Console, MCC Rm}}+5,10\right) \quad \text{(Eqn. F140)}$$

Weight of MCC Room. Assumptions Register Code Number: 4.3.2

$$W_{\text{MCC Rm}}=W_{\text{Cabinet}}\left\lceil\frac{Num_{\text{CPU, MCC Rm}}}{5}\right\rceil+W_{\text{Console}}Num_{\text{Console, MCC Rm}} \quad \text{(Eqn. F141)}$$

$$+Num_{\text{Complement, MCC Rm}}(W_{\text{man}}+W_{\text{Furn}})+1$$

F.6.4 WEAPONS

Weapon Payload Weight. Assumptions /Notes: 4.4

$$W_{\text{Weapon Payload}}=Num_{\text{LAM}}W_{\text{TLAM}}+Num_{\text{ASM}}W_{\text{IDAS}}+Num_{\text{HWT}}W_{\text{HWT}}+Num_{\text{Mine}}W_{\text{SLMM}} \quad \text{(Eqn. F142)}$$

Weapon Payload Volume. Assumptions /Notes: 4.4

$$V_{Weapon\ Payload}=Num_{LAM}V_{TLAM}+Num_{ASM}V_{IDAS}+Num_{HWT}V_{HWT}+Num_{Mine}V_{SLMM} \quad \text{(Eqn. F143)}$$

Weapon Storage Equipment Weight (Excluding Racks). Assumptions /Notes: 4.4.1.2.3

$$W_{Weapon\ Storage\ Equip}=\begin{cases} 0.00014\pi\ Num_{Weapons}w_{HWT}^{2}DDD\ L_{HWT}\rho_{HY80}, & \text{External Single Shot Tube} \\ \dfrac{0.00014\pi\ Num_{Weapons}^{2}w_{HWT}^{2}DDD\ L_{HWT}\rho_{HY80}}{Num_{Torp\ Tube}}, & \text{External Magazine Tubes} \\ 0, & \text{Internal Stowage} \end{cases} \quad \text{(Eqn. F144)}$$

Weapon Handling Gear Weight. Assumptions /Notes: 4.4.1.2.1

$$W_{Hand\ \ Gear}=Num_{Weapon}W_{Torp\ Hand\ \ Gear} \quad \text{(Eqn. F145)}$$

Torpedo (and other Weapons) Stowage Compartment Total Weight:

$$W_{Torp\ Stow}=W_{Hand\ \ Gear}+W_{Weapon\ Payload}+W_{Weapon\ Storage\ Equip} \quad \text{(Eqn. F146)}$$

Torpedo (and other Weapons) Stow Compartment Total Volume. Assumptions /Notes: 4.4.1.2.2

$$V_{Torp\ Stow}=1.2\ V_{Weapon\ Payload} \quad \text{(Eqn. F147)}$$

Torpedo Tube Bank Weight. Assumptions Register Code Number: 4.4.1.2.12

$$W_{Torp\ Tube\ Bank}=\left\lceil\frac{Num_{Torp\ Tube}}{2}\right\rceil\ (W_{Torp\ Tube}+W_{Op\ Fluids}+W_{HWT}) \quad \text{(Eqn. F148)}$$

Torpedo Launch Width. Assumptions Register Code Number: 4.4.1.2.4

$$w_{Torp\ Launch}=\max(D_{ATP},\ D_{21"}+0.5) \quad \text{(Eqn. F149)}$$

Torpedo Launch Weight. Assumptions Register Code Number: 4.4.1.2.11

$$W_{Torp\ Launch}=Num_{Torp\ Tube\ Bank}W_{Torp\ Tube\ Bank}+W_{ATP}+W_{ATP\ Sys\&Air} \quad \text{(Eqn. F150)}$$

Countermeasure Stowage Weight (Per Launcher Bank). Assumptions Register Code Number: 4.4.6.1.2, 4.4.6.1.3 and 4.4.6.2.2

$$W_{CM\ Stow}=\left\lceil\frac{Num_{CM}}{Num_{CM\ Stow\ Bank}}\right\rceil(W_{Bandfish}+W_{SSE}) \quad \text{(Eqn. F151)}$$

F.7 CREW

F.7.1 MANNING COMPOSITION

Number of Engines to Maintain. Assumptions Register Code Number: 5.1.3.2

$$Num_{Engines}=Num_{Non\ Nuke\ Engine}+Num_{Reactors} \quad \text{(Eqn. F152)}$$

Total Mechanical and Electrical Engineering Personnel (Per Watch). Assumptions Register Code Number: 5.1.3.1, 5.1.1.9 and 5.1.3.2

$$\mathrm{Num_{ME}} = \left\lceil \frac{\left(3\ \mathrm{Num_{Engines}}\ \mathrm{W_{Sub}}\right)}{700}\ \frac{\mathrm{Num_{Watch}}+\mathrm{Overhead}}{2} \right\rceil + \frac{\mathrm{Num_{MEO}}+\mathrm{Num_{DMEO}}}{2} \qquad \text{(Eqn. F153)}$$

Men Maintaining Category A MUV/UUVs (per Watch). Assumptions Register Code Number: 5.1.2.3.1 and 5.1.2.3.2

$$\mathrm{Num_{Cat\ A\ Men}} = \left\lceil \frac{\mathrm{Num_{Cat\ A}}}{4} \right\rceil + 1 \qquad \text{(Eqn. F154)}$$

Men Maintaining Category B (and C) UUVs (per Watch). Assumptions Register Code Number: 5.1.2.3.1 and 5.1.2.3.3

$$\mathrm{Num_{Cat\ B\&C\ Men}} = \left\lceil \frac{\mathrm{Num_{Cat\ B}}+\mathrm{Num_{Cat\ C}}}{20} \right\rceil + 2 \qquad \text{(Eqn. F155)}$$

Total Weapons Engineering Personnel (Per Watch). Assumptions Register Code Number: 5.1.2.1.1, 5.1.1.9 and 5.1.2.1.2

$$\mathrm{Num_{WE}} = \left\lceil \frac{\mathrm{Num_{Watch}}+\mathrm{Overhead}}{2} \left(\mathrm{Num_{Torp\ Men}}+\mathrm{Num_{Cat\ A\ Men}}+\mathrm{Num_{Cat\ B\&C\ Men}}\right) \right\rceil \qquad \text{(Eqn. F156)}$$

$$+ \frac{\mathrm{Num_{WEO}}+\mathrm{Num_{DWEO}}}{2} + \mathrm{Num_{CISE}}$$

Total Warfare (Including Officers) Personnel. Assumptions Register Code Number: 5.1.1.1 to 5.1.1.8

$$\mathrm{Num_{Warfare}} = \mathrm{Num_{Elect.\ Sensor}}+\mathrm{Num_{Payload}}+\mathrm{Num_{Comms}}+\mathrm{Num_{Officer}}+\mathrm{Num_{Sonar}} \qquad \text{(Eqn. F157)}$$

F.7.2 ACCOMMODATION

Assumptions Register Code Number: 5.2

F.7.3 STORES

Assumptions Register Code Number: 5.3

F.7.4 MISCELLANEOUS OUTFIT

Assumptions Register Code Number: 5.4

F.7.5 ESCAPE EQUIPMENT

Assumptions Register Code Number: 5.5

F.8 BALLAST

F.8.1 PERMEANT BALLAST

Permanent Ballast Volume. Assumptions Register Code Number: 6.1.1 and 6.1.2

$$V_{\text{Perm Ballast}} = \frac{W_{\text{Perm Ballast}}}{\rho_{\text{Lead}}} \qquad \text{(Eqn. F158)}$$

F.9 ASSUMPTIONS REGISTER

This is a register of all the assumptions (called the Assumptions Register) which were used to create the equations stated in this Appendix.

Table F1 – Assumptions Register

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Input Top Level Variables		1	Y	N		
Strength Input Variables		1.1				
Propulsion Input Variables		1.2				
Payload Input Variables		1.3				
AAW Level	Triple M Mast	1.3.2	Y	N	Only for a self-defence purposes. See: http://en.wikipedia.org/wiki/IDAS_(missile)	n/a
Crew Input Variables		1.4				
Overhead Manning Level	Overhead	1.4.1	Y	N	Assumed.	10%
Unavailable Deck Height	Unavailable Deck Height	1.4.2	Y	N	Based on Assumption in UCL Submarine Design Databook 2012 (pp 140, Section 7.2)	0.3 m
Ballast Input Variables		1.5				
Structures		2				
PH		2.1				
Factor of Safety for DDD	PH	2.1.1	Y	N	Assumed value. Expressed as a factor relative to Diving depth	120%
Diameter of PH	PH	2.1.2	N	Y	Selects best for Usable Volume to Total Volume ratio in PH	
Diameter of PH	PH	2.1.3	N	Y	Taken from Arentzen and Mandel – "Naval Architectural Aspects of Submarine Design" fig 12 pp636	
Total Height of Deck	PH	2.1.4	N	Y	Assume similar to Collins class – source pp5 – "Some Aspects of Submarine Design Part 2." by P N Joubert	2.1 m
Pressure Hull Sizing	PH	2.1.5	N	Y	Taken (modified for twin PH) from Submarine Design Procedure (pp 60 Section 15.2)	
Dome End Bulkheads	PH	2.1.6	N	Y	Taken as 11% of PH Plating & Stiffeners using ‘Pegaso’ SSK in UCL Submarine Design Procedure 2012 (pp 164 Section 11.1)	11% of PH Plating & Stiffeners
Stiffeners Weight	PH	2.1.7	N	Y	Taken as 40% of PH Plating using SSGN ‘Hailstorm’ from Submarine Design Course 2011	40% of PH Plating
Decks, Flats & Pillars Weight	PH	2.1.8	N	Y	Taken as 9% of PH using ‘Pegaso’ SSK in UCL Submarine Design Procedure 2012 (pp 164 Section 11.1)	9% of PH
Major Bulkheads	PH	2.1.9	N	Y	Taken as 11% of PH using ‘Pegaso’ SSK in UCL Submarine Design Procedure 2012 (pp 164 Section 11.1)	11% of PH
Casing		2.2				
Bridge Fin	Fin	2.2.1	Y	N	Only ever 1 bridge fin in all designs	
Length of Fin	Fin	2.2.2	Y	N	Assumed 15% of Length PH (L_{ph})	15%
Height of Fin	Fin	2.2.3	Y	N	Assumed 7.5% of Length PH (L_{ph})	7.5%
Width of Fin	Fin	2.2.4	Y	N	Assumed 3% of Length PH (L_{ph})	3%
Block Coefficient of Fin	Fin	2.2.5	Y	N	Assumed to be 0.67, Based on SSGN ‘Hailstorm’ from UCL Submarine Design Course 2011	67%

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Distance of Casing End to PH End	Casing Body	2.2.6	Y	N	First estimate from 2012 sub design procedure (pp 61-62 Section 15.2.2-3). Casing End Ratio Expressed as a fraction of Casing Diameter	150%
Average Casing Diameter for Twin PH Design Calculations.	Casing Body	2.2.7	Y	N	Is the average of the casing's height and width.	
Volume of Floodable Volume above PH (Exc. Fin)	Casing Body	2.2.8	Y	N	Assume same equation as used by 'Hailstorm' Sub from UCL Submarine Design Exercise 2011	
Height of Floodable Volume above PH (Exc. Fin)	Casing Body	2.2.9	Y	N	Assume same value (1m) as used by 'Hailstorm' Sub from UCL Submarine Design Exercise 2011	1 m
Configuration Floodable Volume above PH (Exc. Fin)	Casing Body	2.2.10	N	Y	Note only applicable in Single Hull Submarines and not double hulled. If D_{so} = 0 then Sub is single hulled	
Sizing of Fwd. and Aft Floodable Section of Casing	Casing Body	2.2.11	N	Y	Taken from UCL Submarine Design procedure 2012 (pp 61-62 Section 15.2.2-3)	
Sizing of Floodable Sections of Casing	Casing Body	2.2.12	N	Y	Taken from UCL Submarine Design procedure 2012 (pp 63-5 Section 15.2.3)	
Weight of Casing	Casing Body	2.2.13	N	Y	Taken from 'Hailstorm' Class SSGN from UCL Submarine Design Course 2011	
Volume of Fwd. Hydroplanes	Fwd. Hydroplanes	2.2.14	N	Y	Assumed Linear Scaling of Boat Displacement using Specs from 'Hailstorm' Class SSGN from UCL Submarine Design Course 2011 to Derive a Scale Factor of 0.377 Tonnes of Hydroplane knot^2	0.377 Te knot^2
Weight of Fwd. Hydroplanes	Fwd. Hydroplanes	2.2.15	Y	N	Assumed to be 105% of Displacement	105%
Number of Fwd. Hydroplanes	Fwd. Hydroplanes	2.2.16	Y	N	Assume Always 2 Fwd. Hydroplanes	2 Hydroplanes
Dimensions of Fwd. Hydroplanes	Fwd. Hydroplanes	2.2.17	N	Y	Scaled to have same Geometry as Bridge Fin	
Volume of Aft Hydroplanes	Aft Hydroplanes	2.2.18	N	Y	Assumed Linear Scaling of Boat Displacement using Specs from 'Hailstorm' Class SSGN from UCL Submarine Design Course 2011 to Derive a Scale Factor of 0.350 Tonnes of Hydroplane knot^2	0.350 Te knot^2
Weight of Aft Hydroplanes	Aft Hydroplanes	2.2.19	Y	N	Assumed to be 105% of Displacement	105%
Number of Aft Hydroplanes	Aft Hydroplanes	2.2.20	Y	N	Assume Always 2 Aft Hydroplanes	2 Hydroplanes
Dimensions of Aft Hydroplanes	Aft Hydroplanes	2.2.21	N	Y	Scaled to have same Geometry as Bridge Fin	
Volume of Rudders	Rudder Planes	2.2.22	N	Y	Assumed Linear Scaling of Boat Displacement using Specs from Thrifty Class SSN from UCL Submarine Design Course 2009 to Derive a Scale Factor of 2.414 Tonnes of Rudder knot^2	2.414 Te knot^2
Weight of Rudders	Rudder Planes	2.2.23	Y	N	Assumed to be 105% of Displacement	105%
Number of Rudder Planes	Rudder Planes	2.2.24	Y	N	Assume Always 2 Rudder planes	2 Rudder Planes
Dimensions of Rudder Planes	Rudder Planes	2.2.25	Y	N	Scaled to have same Geometry as Bridge Fin	
MBT		2.3				
MBT Permeability	MBT	2.3.1	Y	N	Based on Assumption in UCL Submarine Design Procedure 2012 (pp 74, Section 15.9)	95%
MBT Weight (Inc. Flooded Water)	Hover Tank	2.3.2	Y	N	Assumed 120% of Weight of Flooded Water	120.00%
Trim, Hover and Compensation Tanks		2.4				
Trim, Comp and Hover Tank Permeability	Trim, Comp and Hover Tanks	2.4.1	Y	N	Based on Assumption in UCL Submarine Design Procedure 2012 (pp 73, Section 15.8)	95%

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Useable Trim Tank Volume	Trim Tanks	2.4.2	Y	N	Ratio of V_{surf} (Assumed water density variation of 0.02 kg/m^3) [m^3] (Using initial suggested values from UCL Submarine Design Procedure 2012 (pp 73, Section 15.8))	1.25%
Useable Comp Tank Volume	Comp Tanks	2.4.3	Y	N	Ratio of V_{surf} (Assumed water density variation of 0.02 kg/m^3) [m^3] (Using initial suggested values from UCL Submarine Design Procedure 2012 (pp 73, Section 15.8))	3.50%
Useable Hover Tank Volume	Hover Tank	2.4.4	Y	N	Ratio of Volume of PH (Based on 'Hailstorm' from Submarine Design Course 2011)	2.50%
Trim, Comp and Hover Tank Weight (Inc. Flooded Water)	Trim, Comp and Hover Tanks	2.4.5	Y	N	Assumed 120% of Weight of Tank Flooded Water. Assume Trim Tanks gain 20% if required to be 'hard' as part of a 2-tank system	120.00%
Escape Towers		2.5				
Escape Tower Number	Escape Towers	2.5.1	Y	N	Assumed always two per pressure hull (so four for a twin PH design)	2 or 4
Escape Tower Height	Escape Towers	2.5.2	Y	N	Penetrates one deck and casing	
Escape Tower Diameter	Escape Towers	2.5.3	Y	N	Assumed enough space for men to escape unhindered	1.5 m
Escape Tower Weight	Escape Towers	2.5.4	Y	N	Taken from UCL Submarine Databook 2012 'Pegaso' SSK (pp164 Section 11.1)	1 Tonne
Conning Tower		2.6				
Conning Tower Number	Conning Tower	2.6.1	Y	N	Assumed always one per boat	1
Conning Tower Height	Conning Tower	2.6.2	Y	N	Assumed Penetrates at least one deck and casing	
Conning Tower Diameter	Conning Tower	2.6.3	Y	N	Assumed enough space to access	1.5 m
Conning Tower Weight	Conning Tower	2.6.4	Y	N	Taken from Submarine Databook 2012 'Pegaso' SSK (pp 164 Section 11.1)	2 Tonne
Bilge Water Tank		2.7				
Bilge Water Tank Volume	Bilge Water Tank	2.7.1	Y	N	Based on UCL Ship Design Databook 2011, pp107, for a Submarine of 100 crew. Assumed tank must equal 1 day's fresh water.	15 tonnes
Bilge Water Tank Weight (Inc. Flooded Water)	Bilge Water Tank	2.7.2	Y	N	Assumed 105% of Weight of Tank Flooded Water	105 %
Miscellaneous Fittings		2.8				
Electrical Cabling	Distributed	2.8.1	Y	N	Assumed to be 1% of Displacement based on SSN Thrifty's (UCL Submarine Design Course 2009) Weight Breakdown Profile	1% of Displacement
Data Cabling	Distributed	2.8.2	Y	N	1% of Electrical Cabling weight	1% Electrical Cabling Weight
Degaussing System	Distributed	2.8.3	Y	N	Assumed to be 0.25% of Displacement based on SSN Thrifty's (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.25% of Displacement
Pipework	Distributed	2.8.4	Y	N	Assumed to be 0.15% of Displacement based on SSN Thrifty's (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.15% of Displacement
AC Vent System	Distributed	2.8.5	Y	N	Assumed to be 0.25% of Displacement based on SSN Thrifty's (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.25% of Displacement
Lighting System (General & Emergency)	Distributed	2.8.6	Y	N	Assumed to be 0.1% of Displacement based on SSN Thrifty's (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.1% of Displacement
Electrical Glands	Distributed	2.8.7	Y	N	Assumed to be 0.1% of Displacement based on 'Pegaso' SSK (UCL Submarine Databook 2012) Weight Breakdown Profile	0.1% of Displacement
Doors and Hatches	Distributed	2.8.8	Y	N	Assumed to be 0.13% of Displacement based on SSN 'Thrifty' (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.13% of Displacement

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Gratings and Ladders	Distributed	2.8.9	Y	N	Assumed to be 0.2% of Displacement based on SSN ‘Thrifty’ (UCL Submarine Design Course 2009) Weight Breakdown Profile	0.2% of Displacement
Mounts	MC Turbo and MC Motor	2.8.10	Y	N	Assumed to be 0.6% of Displacement based on SSK ‘Pegaso’ (UCL Submarine Databook 2012) Weight Breakdown Profile	0.6% of Displacement
Seats	MC Turbo and MC Motor	2.8.11	Y	N	Assumed to be 1.8% of Displacement based on SSK ‘Pegaso’ (UCL Submarine Databook 2012) Weight Breakdown Profile	1.8 % of Displacement
Insulation and Dampening Weight	Distributed	2.8.11	Y	N	Assumed to be 0.55% of Displacement based on UCL 5000 Te SSN (UCL Submarine Databook 2012) Weight Breakdown Profile	0.55 % of Displacement
Powering		3				
Propeller		3.1				
Relative Rotative Efficiency	Propeller	3.1.1	Y	N	Assumed to be constant at 102% for single shaft and 99% for twin shaft taken from Burcher & Rydill pp117 Table 6.2	102 % or 99%
Propeller Open Water Efficiency	Propeller	3.1.2	Y	N	Assumed to be constant at 65% taken from Burcher & Rydill (1995) pp117 Table 6.2	65%
Transmission Shaft Efficiency	Propeller	3.1.3	Y	N	Assumed to be constant at 98% taken from Burcher and Rydill (1995) pp255	98%
Propeller Rotational Speed	Propeller	3.1.4	Y	N	Assumed to be similar to Victor class, which has a propeller speed of 500 rpm. Source: http://en.wikipedia.org/wiki/Victor-class_submarine	
Hull Efficiency	Casing	3.1.5	N	Y	Equations developed in accordance with data from Burcher and Rydill (1995) Figures 6.7 and 6.8 pp115-116	
Hull Resistance	Casing	3.1.6	Y	N	Equation based on that given by Burcher and Rydill (1995) pp255	
Hydrodynamic Hull Form Coefficient	Casing	3.1.7	Y	N	Equation based on that given by Burcher and Rydill (1995) pp255	
Propeller Weight	Propeller	3.1.8	Y	N	Assumed to be same as UCL 5000 te Submarine from UCL Submarine Databook 2012	80 tonnes
Nuclear Propulsion		3.2				
Thermal Power of Reactor	Reactor Compartment	3.2.1	Y	N	Assumed to be 30% efficient at converting heat to useable energy. From Submarine Design Procedure 2012 (pp 46 Section 9.1)	30%
Flow (and Power) of Steam to Steam Turbines	Reactor Compartment	3.2.2	Y	N	Assumed to be 30% of steam flow. From Submarine Design Procedure 2012 (pp 48 Section 9.2)	30%
Flow (and Power) of Steam to Turbo Generators	Reactor Compartment	3.2.3	Y	N	Assumed to be 70% of steam flow. From Submarine Design Procedure 2012 (pp 48 Section 9.2)	70%
Power lost to transfer of energy to secondary circuit of reactor	Reactor Compartment	3.2.4	Y	N	Assumed to be 90% efficient at transferring energy. From Submarine Design Procedure 2012 (pp 47 Section 9.1)	90%
Ratio of Power from Steam Turbines and Turbo Generators	Reactor Compartment	3.2.5	N	Y	Taken as 70% to 30% from UCL Submarine Design Procedure 2012 (pp 48 Section 9.2)	70% to 30%
Weight of Steam Raising Plant	Reactor Compartment	3.2.6	N	Y	Taken from UCL Submarine Design Procedure 2012 (pp 46 Section 9.1)	
Sizing of Reactor Compartment	Reactor Compartment	3.2.7	N	Y	Taken from UCL Submarine Design Procedure 2012 (pp 46-7 Section 9.1)	
Weight of Shielding in Reactor Compartment	Reactor Compartment	3.2.8	N	Y	Taken from UCL Submarine Design Procedure 2012 (pp 46-7 Section 9.1)	
Flow Rate from Steam Generator	Reactor Compartment	3.2.9	N	Y	Taken from UCL Submarine Design Procedure 2012 (pp 47 Section 9.1)	
Minimum Volume of Turbo Machinery Compartment	MC Turbo	3.2.10	N	Y	Taken from UCL Submarine Design Procedure 2012 (pp 48 Section 9.2)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Batteries		3.3				
Hotel Power	Batteries	3.3.1	Y	N	0.075 kW/tonne displacement + Payload Power taken from Burcher and Rydill pp 256. Add 60kW for High Power Mode). 20 % Assumed for Nuclear Propulsion due to powering pumps etc.	0.075 kW/Tonne + 60 kW
Efficiency Discharging Electrical Energy Stored in Cells	Batteries	3.3.2	Y	N	Assumed to be 95%	95%
Maximum Charging Current of Battery	Batteries	3.3.3	Y	N	Batteries assumed to be HEDBs as described by Submarine Design Procedure (pp72 Section 15.5.10). Used in Charging Equation in UCL Submarine Design Procedure 2012 (pp69 Section 15.5.3)	4000 A
Minimum Charging Current of Battery	Batteries	3.3.4	Y	N	Batteries assumed to be HEDBs as described by Submarine Design Procedure (pp72 Section 15.5.10). Used in Charging Equation in UCL Submarine Design Procedure 2012 (pp69 Section 15.5.3)	300 A
Distance Require to Traverse on Emergency Battery Power Only	Batteries	3.3.5	Y	N	Assumed to be 25 nmi to move away from threat on Battery Power. This is Emergency Propulsion if other Propulsion Types have failed	25 nmi
Margin of Minimum Allowable Charge for Batteries	Batteries	3.3.6	Y	N	Assumed to be 20% based on UCL Submarine Design Procedure 2012 (pp68 Section 15.5.2)	20%
Exponent for Battery Charging Time Model	Batteries	3.3.7	Y	N	Assumed to be 0.08 based on UCL Submarine Design Procedure 2012 (pp68 Section 15.5.2)	0.08
Constant for Battery Charging Time Model	Batteries	3.3.8	Y	N	Assumed to be 32 based on UCL Submarine Design Procedure 2012 (pp68 Section 15.5.3)	32
Weight of Battery Cell	Batteries	3.3.9	Y	N	Assumed to be 0.55 tonnes based on UCL Submarine Design Databook 2012 (pp 77 Section 5.1.3)	0.55 tonnes
Density of Battery Cell	Batteries	3.3.10	Y	N	Assumed to be 2.8 tonnes/m^3 based on UCL Submarine Design Databook 2012 (pp 77 Section 5.1.3)	2.8 tonnes/m^3
Height of Battery Cell	Batteries	3.3.11	Y	N	Assumed to be 1.25 m based on UCL Submarine Design Databook 2012 (pp 77 Section 5.1.3)	2 m
Length of Battery Cell	Batteries	3.3.12	Y	N	Assumed to be 0.45m based on UCL Submarine Design Databook 2012 (pp 77 Section 5.1.3)	0.9 m
Width of Battery Cell	Batteries	3.3.13	Y	N	Assumed to be 0.35m based on UCL Submarine Design Databook 2012 (pp 77 Section 5.1.3)	0.35 m
Charging Time	Batteries	3.3.14	N	Y	Rearranged Equation from UCL Submarine Design Procedure 2012 (pp68 Section 15.5.3)	
Maximum Submerged Time	Batteries	3.3.15	N	Y	Equation from UCL Submarine Design Procedure 2012 (pp70 Section 15.5.5)	
Motor Electrical Efficiency	Batteries	3.3.16	Y	N	Assumed as 95 %	95%
Non-Nuke Propulsion		3.4				
Diesel Power	Diesel Engines	3.4.1				
Diesel Engine and Generator Arrangement	Diesel Engine and Generator	3.4.1.1	N	Y	Note Diesel Engine and Corresponding Generator are rolled into one Block	
Diesel Engine and Generator Sizing	Diesel Engine and Generator	3.4.1.2	Y	N	Equation based on data from UCL Submarine Design Databook 2012 (pp201 Section 12.9.15.1)	
Diesel Engine and Generator Weight	Diesel Engine and Generator	3.4.1.3	Y	N	Equation based on data from UCL Submarine Design Databook 2012 (pp201 Section 12.9.15.1)	
Diesel Engine Power	Diesel Engine and Generator	3.4.1.4	Y	N	Assume half the number of engines can supply hotel power plus power to transit	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Number of Diesel Engines and Generator	Diesel Engine and Generator	3.4.1.5	Y	N	Assume that at least two are required for a level of redundancy	2
Margin of Additional Capacity of Power	Diesel Engine and Generator	3.4.1.6	Y	N	Assumed to be 10%.	10%
Specific Fuel Consumption of Diesel Engine	Diesel Engine and Generator	3.4.1.7	Y	N	Assumed to be 0.25 Tonnes/MWhr	0.25 Tonnes/MWhr
Density of Diesel	Fuel Tanks	3.4.1.8	N	Y	Taken as 0.832 tonne/m^3. See:en.wikipedia.org/wiki/Diesel_fuel	0.832 tonne/m^3
Volume of Fuel Tanks (Dieso)	Fuel Tanks	3.4.1.9	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only)	
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.1.10	Y	N	Assumed to be 10% for Dieso	
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.1.11	Y	N	Assumed to be 5% for Dieso	1%
Compensation for Fuel Tanks	Fuel Tanks	3.4.1.12	N	Y	Seawater assumed to replace volume of used Dieso	
Inhale and Exhaust Mast Weight	Propulsion Masts	3.4.1.13	Y	N	Assumed 1 Tonne Weight	1 Tonne
CCST	CCST Engine	3.4.2				
CCST Engine and Converter Arrangement	CCST Engine and DC Converter	3.4.2.1	N	Y	Note CCST Engine and Corresponding DC Converter are rolled into one Block	
CCST Engine and Converter Sizing	CCST Engine and DC Converter	3.4.2.2	Y	N	Dimensions based on scaling by power scaling^1/3 relative to CCST Engine in Scorpène class	
CCST Engine and Converter Weight	CCST Engine and DC Converter	3.4.2.3	Y	N	Weight based on linear scaling relative to CCST engine in Scorpène class	
CCST Engine Power	CCST Engine and DC Converter	3.4.2.4	Y	N	Assume linear scaling from an estimate based on Scorpène class. 21 MW AIP at 5 knots, 2200 tons. 0.25 MW hotel load.	
Number of CCST Engines	CCST Engine and DC Converter	3.4.2.5	Y	N	Assume that at there is no redundancy due to the high volume of engine	
Margin of Additional Capacity of Power	CCST Engine and DC Converter	3.4.2.6	Y	N	Assumed to be 10%.	10%
Efficiency of CCST Engine	CCST Engine and DC Converter	3.4.2.7	Y	N	Assumed to be 33%. From http://www.mpoweruk.com/steam_turbines.htm	50%
Higher Heating Value for Ethanol	CCST Engine and DC Converter	3.4.2.8	N	Y	0.121 Tonnes of Ethanol/MWhr From http://www.mpoweruk.com/steam_turbines.htm	0.121 Tonnes/MWhr
Ethanol to O2 Consumption Ratio	CCST Engine and DC Converter	3.4.2.9	N	Y	Ratio between Ethanol to O_2 Consumption is 3 Parts Ethanol: 1 Parts O_2	3 to 1
Indiscretion Ratio	CCST Engine and DC Converter	3.4.2.10	N	Y	Taken as 0% as no external O_2 required	0%
Catalytic Decomposition Converter Use	CCST Engine and DC Converter	3.4.2.11	N	Y	HTP and Ethanol can be decomposed to H_2 using a converter (if it is required)	
Catalytic Decomposition Converter Weight	CCST Engine and DC Converter	3.4.2.12	Y	N	Assume linear scaling for to required power. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012 (pp 104 Section 5.6.5)	
Catalytic Decomposition Converter Sizing	CCST Engine and DC Converter	3.4.2.13	Y	N	Assume linear scaling for to required power^1/3. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012 (pp 104 Section 5.6.5)	
Fuel Type	CCST Engine and DC Converter	3.4.2.14	Y	N	Ethanol used in Scorpene Class's Engine so assumed to be used in this CCST engine too	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Density of Ethanol	Fuel Tanks	3.4.2.15	N	Y	Taken as 0.789 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Ethanol	0.789 tonne/m^3
Volume of Fuel Tanks (Ethanol)	Fuel Tanks	3.4.2.16	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only) following loss of primary (Nuclear) power	
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.2.17	Y	N	Assumed to be 10% for Ethanol.	10%
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.2.18	Y	N	Assumed to be 5% for Ethanol	5%
Compensation for Fuel Tanks	Fuel Tanks	3.4.2.19	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	
Density of LOX	O2 Tanks	3.4.2.20	N	Y	Taken as 3.9 tonne/m3 at 90K derived from UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	3.9 tonne/m^3
Volume of O2 Tanks (LOX)	O2 Tanks	3.4.2.21	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only)	
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.2.22	N	Y	Based on Submarine Design Databook 2012 (pp102 Section 5.6.4)	50%
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.2.23	N	Y	Based on Submarine Design Databook 2012 (pp102 Section 5.6.4)	
Compensation for O2 Tanks (Internal LOX)	O2 Tanks	3.4.2.24	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX Internal Storage Sizing	O2 Tanks	3.4.2.25	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
LOX Internal Storage Weight	O2 Tanks	3.4.2.26	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
Compensation for O2 Tanks (External LOX)	O2 Tanks	3.4.2.27	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX External Storage Sizing	O2 Tanks	3.4.2.28	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	
LOX External Storage Weight	O2 Tanks	3.4.2.29	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	
Compensation for O2 Tanks (HTP)	O2 Tanks	3.4.2.30	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	
Density of HTP	O2 Tanks	3.4.2.31	N	Y	Taken as 1.45 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Hydrogen_peroxide	1.45 tonne/m^3
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.2.32	Y	N	Assumed to be 10% for HTP	10%
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.2.33	Y	N	Assumed to be 5% for HTP	5%
HTP Storage Sizing	O2 Tanks	3.4.2.34	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
HTP Storage Weight	O2 Tanks	3.4.2.35	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
Stirling Engine	Stirling Engine	3.4.3				
Stirling Engine and Converter Arrangement	Stirling Engine and DC Converter	3.4.3.1	N	Y	Note Stirling Engine and Corresponding DC Converter are rolled into one Block	
Stirling Engine and Converter Sizing	Stirling Engine and DC Converter	3.4.3.2	Y	N	Dimensions based on scaling by power scaling^1/3 relative to Stirling engine in UCL Submarine Design Databook 2012 (pp 98 Section 5.6.1)	
Stirling Engine and Converter Weight	Stirling Engine and DC Converter	3.4.3.3	Y	N	Weight based on linear scaling relative to Stirling engine in UCL Submarine Design Databook 2012 (pp 99 Section 5.6.1.1)	33%

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Stirling Engine Power	Stirling Engine and DC Converter	3.4.3.4	Y	N	Assume linear scaling from Stirling engine in UCL Submarine Design Databook 2012 (pp 99 Section 5.6.1.1)	2
Efficiency of Stirling Engine	Stirling Engine and DC Converter	3.4.3.5	Y	N	Assume Value From Submarine Technology for the 21st Century – S. Zimmerman pp47 (for a V4 275R engine as used in Gotland class)	10%
Number of Stirling Engines	Stirling Engine and DC Converter	3.4.3.6	Y	N	Assume that at least two engines are required for redundancy	0%
Margin of Additional Capacity of Power	Stirling Engine and DC Converter	3.4.3.7	Y	N	Assumed to be 10%.	
Indiscretion Ratio	Stirling Engine and DC Converter	3.4.3.8	N	Y	Taken as 0% as no external O_2 required	
Catalytic Decomposition Converter Use	Stirling Engine and DC Converter	3.4.3.9	N	Y	HTP and Ethanol can be decomposed to H_2 using a converter (if it is required)	
Catalytic Decomposition Converter Weight	Stirling Engine and DC Converter	3.4.3.10	Y	N	Assume linear scaling for to required power. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012 (pp 104 Section 5.6.5)	0.832 tonne/m^3
Catalytic Decomposition Converter Sizing	Stirling Engine and DC Converter	3.4.3.11	Y	N	Assume linear scaling for to required power^1/3. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012 (pp 104 Section 5.6.5)	0.25 Tonnes/MWhr
Density of Diesel	Fuel Tanks	3.4.3.12	N	Y	Taken as 0.832 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Diesel_fuel	
Specific Fuel Consumption of Dieso for Stirling Engine	Fuel Tanks	3.4.3.13	N	Y	Taken as 0.250 tonnes/MWhr. Submarine Design Databook 2012 (pp99 Section 5.6.1.1)	0.89 Tonnes/MWhr
Volume of Fuel Tanks (Dieso)	Fuel Tanks	3.4.3.14	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only)	5%
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.3.15	Y	N	Assumed to be 10% for Dieso	
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.3.16	Y	N	Assumed to be 5% for Dieso	1%
Compensation for Fuel Tanks (Ethanol)	Fuel Tanks	3.4.3.17	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	3.9 tonne/m^3
Specific Oxidant Consumption	O2 Tanks	3.4.3.18	N	Y	Taken as 0.980 tonnes/MWhr. UCL Submarine Design Databook 2012 (pp99 Section 5.6.1.1)	0.980 tonnes/MWhr
Density of LOX	O2 Tanks	3.4.3.19	N	Y	Taken as 3.9 tonne/m^3 at 90K derived from UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	3.9 tonne/m^3
Volume of O2 Tanks (LOX)	O2 Tanks	3.4.3.20	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only)	5%
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.3.21	N	Y	Based on UCL Submarine Design Databook 2012 (pp102 Section 5.6.4)	50%
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.3.22	N	Y	Based on UCL Submarine Design Databook 2012 (pp102 Section 5.6.4)	
Compensation for O2 Tanks (Internal LOX)	O2 Tanks	3.4.3.23	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX Internal Storage Sizing	O2 Tanks	3.4.3.24	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
LOX Internal Storage Weight	O2 Tanks	3.4.3.25	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
Compensation for O2 Tanks (External LOX)	O2 Tanks	3.4.3.26	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX External Storage Sizing	O2 Tanks	3.4.3.27	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
LOX External Storage Weight	O2 Tanks	3.4.3.28	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	
Compensation for O2 Tanks (HTP)	O2 Tanks	3.4.3.29	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	
Density of HTP	O2 Tanks	3.4.3.30	N	Y	Taken as 1.45 tonne/m3 at room temperature. See: http://en.wikipedia.org/wiki/Hydrogen_peroxide	1.45 tonne/m3
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.3.31	Y	N	Assumed to be 10% for HTP	10%
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.3.32	Y	N	Assumed to be 5% for HTP	5%
HTP Storage Sizing	O2 Tanks	3.4.3.33	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
HTP Storage Weight	O2 Tanks	3.4.3.34	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
Fuel Cell	Fuel Cells	3.4.4				
Higher Heating Value for Fuel Cell Reaction	Fuel Cells	3.4.4.1	N	Y	Taken as 285.84 kJ/mol from http://en.wikipedia.org/wiki/Proton_exchange_membrane_fuel_cell	285.84 kJ/mol
Efficiency for Fuel Cell (PEM)	Fuel Cells	3.4.4.2	Y	N	Taken as 46% from http://www.chfcc.org/FuelCellBus/P076_PureMotion%20120.pdf	46%
Efficiency for Fuel Cell (PEM using Methanol)	Fuel Cells	3.4.4.3	Y	N	Assume Scaling from Figures for APEM from Submarine Technology for the 21st Century – Zimmerman pp66	40%
Fuel Cell (PEM) and Converter Arrangement	Fuel Cells	3.4.4.4	N	Y	Note Fuel Cell (APEM) and Corresponding DC Converter are rolled into one Block	
Fuel Cell (PEM) and Converter Sizing	Fuel Cells	3.4.4.5	Y	N	Dimensions based on scaling by power scaling^1/3 relative to Fuel Cell (APEM). 120kw, 290 Volt Fuel Cell stack from PureMotion http://www.chfcc.org/FuelCellBus/P076_PureMotion%20120.pdf	
Fuel Cell (PEM) and Converter Weight	Fuel Cells	3.4.4.6	Y	N	Weight based on linear scaling relative to Fuel Cell (APEM). 120kw, 290 Volt Fuel Cell stack from PureMotion http://www.chfcc.org/FuelCellBus/P076_PureMotion%20120.pdf	73%
Fuel Cell (PEM) Power	Fuel Cells	3.4.4.7	Y	N	Assume linear scaling from Fuel Cell (APEM). 120kw, 290 Volt Fuel Cell stack from PureMotion http://www.chfcc.org/FuelCellBus/P076_PureMotion%20120.pdf	63%
Efficiency for Fuel Cell (APEM)	Fuel Cells	3.4.4.8	Y	N	Taken from “Submarine Technology for the 21st Century” – Zimmerman pp66	
Efficiency for Fuel Cell (APEM using Methanol)	Fuel Cells	3.4.4.9	Y	N	Taken from “Submarine Technology for the 21st Century” – Zimmerman pp66	10%
Fuel Cell (APEM) and Converter Arrangement	Fuel Cells	3.4.4.10	N	Y	Note 7x Fuel Cell (APEM) + 1 Control Unit and Corresponding DC Converter are rolled into one Block	
Fuel Cell (APEM) and Converter Sizing	Fuel Cells	3.4.4.11	Y	N	Dimensions based on scaling by power scaling^1/3 relative to Fuel Cell (APEM). 70 kW SFE 280V(solid polymer electrolyte) cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.1)	
Fuel Cell (APEM) and Converter Weight	Fuel Cells	3.4.4.12	Y	N	Weight based on linear scaling relative to Fuel Cell (APEM) 70 kW SFE 280V(solid polymer electrolyte) cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.1)	
Fuel Cell (APEM) Power	Fuel Cells	3.4.4.13	Y	N	Assume linear scaling from Fuel Cell (APEM) 70 kW SFE 280V(solid polymer electrolyte) cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.1)	
Efficiency for Fuel Cell (AFC)	Fuel Cells	3.4.4.14	Y	N	Taken from “Submarine Technology for the 21st Century” – Zimmerman pp66	77%
Fuel Cell (AFC) and Converter Arrangement	Fuel Cells	3.4.4.15	N	Y	Note 7x Fuel Cell (AFC) + 1 Control Unit and Corresponding DC Converter are rolled into one Block	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Fuel Cell (AFC) and Converter Sizing	Fuel Cells	3.4.4.16	Y	N	Dimensions based on scaling by power scaling^1/3 relative to Fuel Cell (AFC) 52 kW 378V cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.2)	
Fuel Cell (AFC) and Converter Weight	Fuel Cells	3.4.4.17	Y	N	Weight based on linear scaling relative to Fuel Cell (AFC) 52 kW 378V cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.2)	
Fuel Cell (AFC) Power	Fuel Cells	3.4.4.18	Y	N	Assumed linear scaling from Fuel Cell (AFC) 52 kW 378V cell stack in UCL Submarine Design Databook 2012 (pp207 Section 5.6.7.2)	
Efficiency for Fuel Cell (PAFC)	Fuel Cells	3.4.4.19	Y	N	Taken from “Submarine Technology for the 21st Century” – Zimmerman pp66	50%
Fuel Cell (PAFC) and Converter Arrangement	Fuel Cells	3.4.4.20	N	Y	Note Fuel Cell (PAFC) and Corresponding DC Converter are rolled into one Block	
Fuel Cell (PAFC) and Converter Sizing	Fuel Cells	3.4.4.21	Y	N	Dimensions based on scaling by power scaling^1/3 relative to Fuel Cell (PAFC). 500 kW, 500V Phosphoric Acid Fuel cell stack in UCL Submarine Design Databook 2012	
Fuel Cell (PAFC) and Converter Weight	Fuel Cells	3.4.4.22	Y	N	Weight based on linear scaling relative to Fuel Cell (PAFC). 500 kW, 500V Phosphoric Acid Fuel cell stack in UCL Submarine Design Databook 2012	
Fuel Cell (PAFC) Power	Fuel Cells	3.4.4.23	Y	N	Assumed linear scaling from Fuel Cell stack (PAFC). 500 kW, 500V Phosphoric Acid Fuel cell stack in UCL Submarine Design Databook 2012	
Fuel Cell Redundancy	Fuel Cells	3.4.4.24	N	Y	Many individual cells so no need to double up on every cell for redundancy for each cell	
Margin of Additional Capacity of Power	Fuel Cells	3.4.4.25	Y	N	Assumed to be 10%.	10%
Indiscretion Ratio	Fuel Cells	3.4.4.26	N	Y	Taken as 0% as no external O2 required	0%
Catalytic Decomposition Converter Use	Fuel Cells and DC Converter	3.4.4.27	N	Y	HTP and Methanol can be decomposed to H_2 using a converter (if it is required)	
Catalytic Decomposition Converter Weight	Fuel Cells and DC Converter	3.4.4.28	Y	N	Assumed linear scaling for to required power. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012	
Catalytic Decomposition Converter Sizing	Fuel Cells and DC Converter	3.4.4.29	Y	N	Assumed linear scaling for to required power^1/3. Relative to one provided for fuel cells in UCL Submarine Design Databook 2012	
Density of Methanol	Fuel Tanks	3.4.4.30	N	Y	Taken as 0.7918 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Methanol	0.7918 tonne/m^3
Volume of Fuel Tanks	Fuel Tanks	3.4.4.31	Y	N	Assumed for a transit distance of 2000 nm to nearest friendly port (For SSN sizing only)	
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.32	Y	N	Assumed to be 10% for Methanol.	10%
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.33	Y	N	Assumed to be 5% for Methanol	5%
Compensation for Fuel Tanks (Methanol)	Fuel Tanks	3.4.4.34	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	
Density of CNF	Fuel Tanks	3.4.4.35	N	Y	Taken as 0.04 tonne/m^3 at room temperature extracted from UCL Submarine Design Databook 2012 (pp 108 Section 5.6.7.3)	0.06 tonne/m^3
Volume of Fuel Tanks	Fuel Tanks	3.4.4.36	Y	N	Assumed for a transit distance of 2000 nm to nearest friendly port (For SSN sizing only)	
Pressure of Stored H2	Fuel Tanks	3.4.4.37	Y	N	120 bar. Based on Submarine Design Databook 2012 (pp 106 Section 5.6.6.2)	120 bar
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.38	Y	N	Assumed to be 10%	10%
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.39	Y	N	Assumed to be 5%	5%
Compensation for Fuel Tanks (CNF)	Fuel Tanks	3.4.4.40	Y	N	Assumed to require Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Density of MH	Fuel Tanks	3.4.4.41	N	Y	Taken as 0.09 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Hydrogen_Storage	0.09 tonne/m^3
Volume of Fuel Tanks	Fuel Tanks	3.4.4.42	Y	N	Assumed for a transit distance of 2000 nmi to nearest friendly port (For SSN sizing only)	
Weight of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.43	N	Y	Data taken from "Military Applications for H2 Storage" – Browning	
Vol of Fuel Tanks Structure Relative to Fuel	Fuel Tanks	3.4.4.44	N	Y	Data taken from "Military Applications for H2 Storage" – Browning	5%
Compensation for Fuel Tanks (MH)	Fuel Tanks	3.4.4.45	N	Y	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
Specific Oxidant Consumption	O2 Tanks	3.4.4.46	N	Y	Taken as 0.890 tonnes/MWhr from UCL Submarine Design Databook 2012 (pp 99 Section 5.6.1.1)	0.98 tonnes/MWhr
Density of LOX	O2 Tanks	3.4.4.47	N	Y	Taken as 3.9 tonne/m^3 at 90K derived from UCL Submarine Design Databook 2012 (pp102 Section 5.6.4)	3.9 tonne/m^3
Volume of O2 Tanks (LOX)	O2 Tanks	3.4.4.48	Y	N	Assumed for a transit distance of 2000 nm to nearest friendly port (For SSN sizing only)	2000 nm
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.4.49	N	Y	Based on UCL Submarine Design Databook 2012 (pp102 Section 5.6.4)	50%
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.4.50	N	Y	Based on UCL Submarine Design Databook 2012 (pp102 Section 5.6.4)	
Compensation for O2 Tanks (Internal LOX)	O2 Tanks	3.4.4.51	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX Internal Storage Sizing	O2 Tanks	3.4.4.52	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
LOX Internal Storage Weight	O2 Tanks	3.4.4.53	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.1)	
Compensation for O2 Tanks (External LOX)	O2 Tanks	3.4.4.54	Y	N	Independent Compensation Required (Assumed to be expressed as bigger comp tanks)	
LOX External Storage Sizing	O2 Tanks	3.4.4.55	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	
LOX External Storage Weight	O2 Tanks	3.4.4.56	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp 102 Section 5.6.4.2)	
Compensation for O2 Tanks (HTP)	O2 Tanks	3.4.4.57	N	Y	Stored in flexible vessel so automatically compensates. See UCL Submarine Design Procedure 2012 (pp44 Section 8.2.2)	
Density of HTP	O2 Tanks	3.4.4.58	N	Y	Taken as 1.45 tonne/m^3 at room temperature. See: http://en.wikipedia.org/wiki/Hydrogen_peroxide	1.45 tonne/m^3
Weight of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.4.59	Y	N	Assumed to be 10% for HTP	10
Vol of O2 Tanks Structure Relative to Fuel	O2 Tanks	3.4.4.60	Y	N	Assumed to be 5% for HTP	5
HTP Storage Sizing	O2 Tanks	3.4.4.61	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
HTP Storage Weight	O2 Tanks	3.4.4.62	N	Y	Taken from data for Tanks in UCL Submarine Design Databook 2012 (pp103 Section 5.6.4.3)	
Propulsion Equipment Compartments		3.5				
Condenser		3.5.1				
Size of Condenser	Condensers	3.5.1.1	Y	N	Assume condenser sizing based on 5000 tonne SSN from UCL Submarine Design Databook 2012 (pp 210 Section 12.9.16.29) and fitting into deck height (DH)	
Number of Condensers	Condensers	3.5.1.2	Y	N	Assume that at least two are required for a level of redundancy	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Condenser Weight	Condensers	3.5.1.3	Y	N	Assume Equation based on scaling 25 tonnes/ Condenser from 5000 tonne SSN in UCL Submarine Design Databook 2012 (pp 175 Section 12.1)	
Switchboard Room		3.5.2				
Switchboard and Breaker Sizing	Switchboard Room	3.5.2.1	N	Y	Based on equations from UCL Submarine Design Databook 2012 (pp 78 Section 5.1.4)	
Switchboard and Breaker Weight	Switchboard Room	3.5.2.2	N	Y	Based on equations from UCL Submarine Design Databook 2012 (pp 78 Section 5.1.4)	
Switchboard Room Access	Switchboard Room	3.5.2.3	Y	N	Assume 1 m corridor for access	1 m
RC Access Tunnel		3.5.3				
RC Access Tunnel Height	RC Access Tunnel	3.5.3.1	N	Y	Must be one deck high to allow for a person to move through the access tunnel	
RC Access Tunnel Height	RC Access Tunnel	3.5.3.2	N	Y	Must be same length as RC	
RC Access Tunnel Number	RC Access Tunnel	3.5.3.3	Y	N	Assume one access tunnel per pressure hull	
RC Access Tunnel Weight	RC Access Tunnel	3.5.3.4	Y	N	Assume negligible Weight of 0.01 tonnes	0.01 tonnes
Turbo Generators		3.5.4				
Number of Turbo Generators	Turbo Generators	3.5.4.1	Y	N	Assume that at least two are required for a level of redundancy. Number of TGs can be increased to fit inside PH as well.	2
Diameter of Turbo Generators	Turbo Generators	3.5.4.2	N	Y	Equations to determine size and number of TGs are extracted from UCL Submarine Design Databook 2012 (pp201 section 12.9.15.1)	
Weight of Turbo Generators	Turbo Generators	3.5.4.3	N	Y	Equation based on data extracted from UCL Submarine Design Databook 2012 (pp201 section 12.9.15.1)	
Rafts	Turbo Generators	3.5.4.4	Y	N	Scaled from UCL 5000 Tonne SSN (UCL Submarine Design Databook 2012) Using Maximum Power (of 15,000SHP and 52 te weight of Rafting)	
Steam Turbines		3.5.5				
Number of Steam Turbines	Steam Turbines	3.5.5.1	Y	N	Assume that at least two are required for a level of redundancy. Assume Steam turbine weight based on “RGP model” by Tim MacDonald for UCL DRC	2
Size of Steam Turbines	Steam Turbines	3.5.5.2	Y	N	Assume Steam turbine sizing based on “RGP model” by Tim MacDonald for UCL DRC	
Weight of Steam Turbines	Steam Turbines	3.5.5.3	Y	N	Assumed Steam turbine sizing based on “RGP model” by Tim MacDonald for UCL DRC	
Motor Generators		3.5.6				
Number of Motors	Main Electrical Motors	3.5.6.1	Y	N	Assumed at least 2 motors needed (http://archive.hnsa.org/doc/fleetsub/diesel/chap13.htm)	2
Motor Size	Main Electrical Motors	3.5.6.2	N	Y	Equations derived from UCL Submarine Design Databook 2012 (pp 75 Section 5.1.1)	
Motor Weight	Main Electrical Motors	3.5.6.3	N	Y	Equations derived from UCL Submarine Design Databook 2012 (pp 75 Section 5.1.1)	
Gearbox and Clutch		3.5.7				
Number of Gearbox	Gearbox and Clutch	3.5.7.1	Y	N	Assumed 1 Gearbox and Clutch per propulsion shaft	
Gearbox and Clutch Diameter	Gearbox and Clutch	3.5.7.2	Y	N	Assume scales linearly to power^1/2 based on benchmark from 5000 SSN in UCL Submarine Design Databook 2012 pp205 Section 12.9.16.8 (has 15000 SHP)	
Gearbox and Clutch Weight	Gearbox and Clutch	3.5.7.3	Y	N	Assumed scales linearly to power^1/2 based on benchmark from 5000 SSN in UCL Submarine Design Databook 2012 pp205 Section 12.9.16.8 (has 15000 SHP)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Motor Generators		3.5.8				
Number of Motors	Motor Generators	3.5.8.1	Y	N	Assumed at least 2 motors needed (http://archive.hnsa.org/doc/fleetsub/diesel/chap13.htm)	2
Motor Size	Motor Generators	3.5.8.2	N	Y	Based on equations from UCL Submarine Design Databook 2012 (pp 131 Section 6.2.1.1)	
Motor Weight	Motor Generators	3.5.8.3	N	Y	Based on equations from UCL Submarine Design Databook 2012 (pp 131 Section 6.2.1.1)	
Auxiliary Machinery		3.6				
Air Plant		3.6.1				
High Pressure Compressor	Air Plant	3.6.1.1	Y	N	Assumed 10 hours recharge time	10 hours
High Pressure Air Pressure	Air Plant	3.6.1.2	Y	N	High Pressure Air at 200 Bar. Taken from UCL Submarine Design Databook 2012 (pp 117 Section 6.1.1)	200 Bar
Number of Compressors	Air Plant	3.6.1.3	N	Y	From UCL Submarine Design Databook 2012 (pp 117 Section 6.1.1)	
Total Weight of High Pressure Air	Air Plant	3.6.1.4	N	Y	Equation From Ship Design Databook 2011 (pp 58 Section 3.3.7)	
Air Plant Sizing	Air Plant	3.6.1.5	N	Y	Low and High Pressure Compressor Sizing Data from UCL Submarine Design Databook 2012 (pp 117 Section 6.1.1.1)	
Air Plant Weight	Air Plant	3.6.1.6	N	Y	Low and High Pressure Compressor Weight Data from UCL Submarine Design Databook 2012 (pp 117 Section 6.1.1.1)	
High Pressure Air Supply System Weight	Air Supply	3.6.1.7	Y	N	Assumed to be 2 Tonnes, same as ‘Hailstorm’ SSGN (UCL Submarine Design Course 2011)	2 Tonnes
High Pressure Air Bottle Volume	Air Supply	3.6.1.8	Y	N	Equation From UCL Submarine Design Databook 2012 (pp 117 Section 6.1.1)	
Emergency Air Supply System Weight	Air Supply	3.6.1.9	Y	N	Assumed to be 1 Tonne	1 Tonnes
Emergency Pressure Air Bottle Volume	Air Supply	3.6.1.10	Y	N	Equation From UCL Submarine Design Databook 2012 (pp 119 Section 6.1.2)	
Low Pressure Air Supply System Weight	Air Supply	3.6.1.11	Y	N	Assumed to be 4 Tonnes, same as ‘Hailstorm’ SSGN (Submarine Design Course 2011)	4 Tonnes
Chilled Water Plant		3.6.2				
Chilled Water Unit Power	Chilled Water Plant	3.6.2.1	N	Y	Chilling Power Equation from UCL Submarine Design Databook 2012 given as 56 kW/Unit (pp129 Section 6.1.8)	56 kW/Unit
Chilled Water Plant Power	Chilled Water Plant	3.6.2.2	Y	N	Equation given in Submarine Design Databook 2012 (pp129 Section 6.1.8) as $0.075kW/m^3$ of Propulsion Machinery	$0.075kW/m^3$
Chilled Water Unit Sizing	Chilled Water Plant	3.6.2.3	N	Y	Sizing Equations derived in UCL Submarine Design Databook 2012 (pp129 Section 6.1.8)	
Weight of Chilled Water Unit	Chilled Water Plant	3.6.2.4	N	Y	Weight Equation given in UCL Submarine Design Databook 2012 (pp129 Section 6.1.8) as 3 tonnes/unit	3 Tonnes/Unit
Steam Feed		3.6.3				
Number of Plants	Steam Feed	3.6.3.1	Y	N	Assumed to be 2 Plants, same as ‘Hailstorm’ from Submarine Design Course 2011	2
Sizing of Steam Feed	Steam Feed	3.6.3.2	N	Y	From “RGP Model” By Tim McDonald as 13.4 Tonnes	13.4 Tonnes
Weight of Steam Feed	Steam Feed	3.6.3.3	Y	N	.Assumed as $2 m^3$	$2 m^3$
Hydraulic Plant		3.6.4				
Hydraulic System Weight	Hydraulic Plant	3.6.4.1	Y	N	Assumed to be 3.6 Tonnes, same as ‘Hailstorm’ SSGN (UCL Submarine Design Course 2011)	3.6 Tonnes
Hydraulic Plant Dimensions	Hydraulic Plant	3.6.4.2	N	Y	Sizing Equations in UCL Submarine Design Databook 2012 (pp121 Section 6.1.4)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Hydraulic Plant Weight	Hydraulic Plant	3.6.4.3	N	Y	Weight Equation in UCL Submarine Design Databook 2012 (pp121 Section 6.1.4)	
Ballast and Trim Plant		3.6.5				
Ballast and Trim System Weight	Ballast and Trim Plant	3.6.5.1	Y	N	Assumed Linear Scaling using Boat Displacement Specs from ‘Hailstorm’ Class SSGN from Submarine Design Course 2011	0.0036 Te /Te of Displacement
Trim Pump Weight	Ballast and Trim Plant	3.6.5.2	N	Y	Weight Data from UCL Submarine Design Databook 2012 (pp126 Section 6.1.5.2)	
Trim Pump Dimensions	Ballast and Trim Plant	3.6.5.3	N	Y	Dimensions from Data in UCL Submarine Design Databook 2012 (pp126 Section 6.1.5.2)	
Number of Trim Pumps	Ballast and Trim Plant	3.6.5.4	N	Y	Based on System Design in UCL Submarine Design Databook 2012 (pp124 Section 6.1.5)	
Ballast Pump Weight	Ballast and Trim Plant	3.6.5.5	N	Y	Weight Data from UCL Submarine Design Databook 2012 (pp125 Section 6.1.5.1)	
Ballast Pump Dimensions	Ballast and Trim Plant	3.6.5.6	N	Y	Dimensions from Data in UCL Submarine Design Databook 2012 (pp125 Section 6.1.5.1)	
Number of Ballast Pumps	Ballast and Trim Plant	3.6.5.7	N	Y	Based on System Design in UCL Submarine Design Databook 2012 (pp124 Section 6.1.5)	
Bilge Plant		3.6.6				
Bilge System Weight	Bilge Plant	3.6.6.1	Y	N	Assumed Linear Scaling using Boat Displacement Specs from ‘Hailstorm’ Class SSGN from UCL Submarine Design Course 2011	0.0049 Te /Te of Displacement
Bilge Pump Weight	Bilge Plant	3.6.6.2	N	Y	Weight Data from UCL Submarine Design Databook 2012 (pp126 Section 6.1.5.2)	
Bilge Pump Dimensions	Bilge Plant	3.6.6.3	N	Y	Dimensions from Data in UCL Submarine Design Databook 2012 (pp126 Section 6.1.5.2)	
Air Conditioning Plant		3.6.7				
Rate of Air Change	AC Plant	3.6.7.1	Y	N	Assumed to be 40 Changes of Air every Hour	40 Changes/hr
AC Unit Weight	AC Plant	3.6.7.2	N	Y	Weight Data from UCL Submarine Design Databook 2012 (pp133 Section 63.1)	
AC Unit Dimensions	AC Plant	3.6.7.3	N	Y	Dimensions from Data in UCL Submarine Design Databook 2012 (pp133 Section 6.3.1)	
AC Unit Capacity	AC Plant	3.6.7.4	N	Y	Data from UCL Submarine Design Databook 2012 (pp133 Section 6.3.1)	2 m^3/sec
CO_2 Absorption Unit Weight	AC Plant	3.6.7.5	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.6)	
CO_2 Absorption Unit Dimensions	AC Plant	3.6.7.6	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.6)	
CO_2 Absorption Unit Number	AC Plant	3.6.7.7	Y	N	Assumed 2 $C0_2$ Absorption Units	2 Units
O_2 Generation Unit Weight	AC Plant	3.6.7.8	N	Y	Data from UCL Submarine Design Databook 2012 (pp135 Section 6.3.7)	
O_2 Generation Unit Dimensions	AC Plant	3.6.7.9	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.7)	
O_2 Generation Unit Number	AC Plant	3.6.7.10	Y	N	Assumed 2 0_2 Generation Units	2 Units
Auxiliary Steam Plant		3.6.8				
Aux Steam Plant Volume	Aux Steam Plant	3.6.8.1	Y	N	Assumed Linear Scaling using Boat Displacement Specs from SSN Thrifty from UCL Submarine Design Course 2009	
Aux Steam Plant Weight	Aux Steam Plant	3.6.8.2	Y	N	Assumed Linear Scaling using Boat Displacement Specs from SSN Thrifty from UCL Submarine Design Course 2009	
Garbage Ejector		3.6.9				

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Garbage Ejector Weight	Garbage Ejector	3.6.9.1	Y	N	Assumed Linear Scaling using Boat Displacement Specs from SSGN ‘Hailstorm’ from UCL Submarine Design Course 2011	
Hydroplane and Steering Equipment		3.6.10				
Hydroplane and Steering Equipment Weight	Hydroplane and Steering Equipment Ejector	3.6.10.1	Y	N	Assumed Linear Scaling using Boat Displacement Specs from SSGN ‘Hailstorm’ from UCL Submarine Design Course 2011	
Payload		4				
UUV		4.1				
Category A		4.1.1				
Category A Capability	Category A UUV Fleet	4.1.1.1	N	Y	Based on pre-calculated results from USGOT	
Category A Number	Category A UUV Fleet	4.1.1.2	N	Y	Based on pre-calculated results from USGOT, must be greater or equal to 4, when considering high UUV resource missions	4 Cat. A UUVs
Category A Sizing Equation	Category A UUV Fleet	4.1.1.3	Y	N	Assumed Equations derived from USGOT work for the dimensions for a Generic UUV	
Category A LARS Weight	Category A LARS	4.1.1.4	Y	N	Assumed based on that LARS Weight/UUV is 50% Cat A UUV weight	50%
Category A Launch Tube Weight (if Single Interface LARS)	Category A LARS	4.1.1.5	N	Y	Only one Launch Tube required	1 Cat. A Launch Tube
Category A Launch Tube Weight (if Self-Contained LARS)	Category A LARS	4.1.1.6	N	Y	One Launch Tube required/ Cat. A UUV	1 Cat. A Launch Tube/UUV
Category A Launch Tube Weight (if internally stowed, Containing UUV)	Category A LARS	4.1.1.7	Y	N	Assumed to be similar to Trident Missile Tubes – i.e. construct small PH based on equations in UCL Submarine Design Databook 2012	
Category A Launch Tube Weight (if internally stowed, No UUV)	Category A LARS	4.1.1.8	Y	N	Assumed to be full of seawater	
Category A Launch Tube Volume	Category A LARS	4.1.1.9	Y	N	Assumed to be a cylinder into which Cat. A UUV just fits. Plus a 20% margin for access	20%
Category A Launch Tube Weight (if externally stowed)	Category A LARS	4.1.1.10	Y	N	Assumed to Cat. A UUVs to be neutrally buoyant so has density of sea water	
Category A Launch Tube Separation	Category A LARS	4.1.1.11	Y	N	Assumed 0.5m separation between tubes	0.5 m
Category A Launch Tube Arrangement	Category A LARS	4.1.1.12	Y	N	Assumed 2 rows of launch tubes (if Self Contained)	2 columns
Category A Launch Equipment	Category A LARS	4.1.1.13	Y	N	Assumed 1 ATP per Launch tube	1 ATP/Launch
Category A Handling Equipment Weight	Category A LARS	4.1.1.14	Y	N	Assumed Weight/UUV of 20% of Cat. A Weight	20%
Category A Handling Equipment Volume	Category A LARS	4.1.1.15	Y	N	Assumed Volume/UUV of 20% of Cat. A Volume	20%
Category A Internal Garage Weight (if required)	Category A LARS	4.1.1.16	Y	N	Assumed of 1 tonne per Cat A UUV for machinery to move UUVs In/Out PH. Assume 2 sets of machinery for redundancy	2 x 1 tonne / Cat. A UUV
Category A Internal Garage Volume (if required)	Category A LARS	4.1.1.17	Y	N	Assumed to be sized to hold 2 Cat. A UUVs	
Category A Storage Volume (Externally Stowed)	Category A LARS	4.1.1.18	Y	N	Assumed extra 20% penalty for installation outside PH	20%
Category A Storage Volume (Self Contained LARS)	Category A LARS	4.1.1.19	Y	N	Assumed 20% penalty due to less efficient arrangement of Cat. A UUVs	20%

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Category A Storage Volume	Category A LARS	4.1.1.20	Y	N	Assumed 50% penalty due to the need for access	50%
Category A Storage & Launch Arrangement	Category A LARS	4.1.1.21	Y	N	Assume that the Cat A LARS and Stow Compartments can be combined into one compartment.	
Category A Recharge Power	Category A LARS	4.1.1.22	Y	N	Assumed Linear Relationship for UUV Displacement thus Stored Energy (see USGOT Notes) and Recharge Power. Data Point from "UUV Docking and Recharging Station: Demonstration Results and Next Steps" – R. Granger Demonstrating a LARS for a Bluefin 12	5.7692 kW/Tonne
Category A Recharge Time	Category A LARS	4.1.1.23	Y	N	Data Point from "UUV Docking and Recharging Station: Demonstration Results and Next Steps" – R. Granger Demonstrating a LARS for a Bluefin 12. Assume Equal for all UUVs. Conservatively assume 20% UUVs Simultaneously recharging (Note allows for operational flexibility)	12 hours
Category B and C		4.1.2				
Category B and C Capability	Category B and C UUV Fleet	4.1.2.1	N	Y	Based on pre-calculated results from USGOT	
Category B and C Number	Category B and C UUV Fleet	4.1.2.2	Y	N	Assumed based on experience using USGOT to have 30 Cat. B and 30 Cat. C UUVs, when considering high UUV resource missions	30 Cat. B and 30 Cat. C UUVs
Category B UUV Weight	Category B and C UUV Fleet	4.1.2.3	Y	N	Assumed to be 'Hugin 1000' UUV with 0.850 tonnes Weight	0.850 tonnes
Category C UUV Weight	Category B and C UUV Fleet	4.1.2.4	Y	N	Assumed to be generic "fire and forget" UUV with 0.250 tonnes Weight	0.250 tonnes
Category B and C Launch Tube Weight	Category B and C LARS	4.1.2.5	Y	N	Assumed for Launch Tube Weight/UUV linear scaling of 21" Torpedo Tube, for UUV Weight relative to a torpedo (Spearfish) Weight (Given in UCL Submarine Design Databook 2012)	
Category B and C Launch Tube Volume	Category B and C LARS	4.1.2.6	Y	N	Assumed for Launch Tube Weight/UUV linear scaling of 21" Torpedo Tube, for UUV Weight relative to a torpedo (Spearfish) Weight (Given in UCL Submarine Design Databook 2012)	
Category B and C Launch Tube Number	Category B and C LARS	4.1.2.7	Y	N	Assumed 6 UUVs/ Launch Tube	6 UUV/ Launch Tube
Category B and C Launch Tube Separation	Category B and C LARS	4.1.2.8	Y	N	Assumed 0.5m separation between tubes	0.5m
Category B and C Launch Tube Arrangement	Category B and C LARS	4.1.2.9	Y	N	Assumed 2 columns of launch tubes. 2 Banks of tubes, One starboard and one port.	2 columns
Category B and C Launch Equipment	Category B and C LARS	4.1.2.10	Y	N	Assumed 1 ATP per Launch tube and scaling relative to the equipment for a 21" torpedo tube	1 ATP/Launch
Category B and C Handling Equipment Weight	Category B and C LARS	4.1.2.11	Y	N	Assumed Weight/UUV of 20% of Cat. B Weight (As it's greater than Cat C's Weight)	20%
Category B and C Handling Equipment Volume	Category B and C LARS	4.1.2.12	Y	N	Assumed Volume/UUV of 20% of Cat. B Volume (As it's greater than Cat C's volume)	20%
Category B and C Storage Volume	Category B and C LARS	4.1.2.13	Y	N	Assumed 50% penalty due to the need for access	50%
Category B and C Storage Location	Category B and C LARS	4.1.2.14	Y	N	Assume to always to be internal, similar to traditional torpedo storage	
Category B and C Recharge Power	Category B and C LARS	4.1.2.15	Y	N	Assumed Linear Relationship for UUV Displacement thus Stored Energy (see USGOT Notes) and Recharge Power. Data Point from "ASNE Launch and Recovery Symposium" – R. Granger Demonstrating a LARS for a Bluefin 12	5.7692 kW/Tonne

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Category B and C Recharge Time	Category B and C LARS	4.1.2.16	Y	N	Data Point from "ASNE Launch and Recovery Symposium" – R. Granger Demonstrating a LARS for a Bluefin 12. Assume Equal for all UUVs. Conservatively assume 20% UUVs Simultaneously recharging (Note allows for operational flexibility)	12 hours
Electronic Payload		4.2				
Bow Sonar	Bow Sonar	4.2.1				
Bow Sonar Sizing	Bow Sonar	4.2.1.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp56 Section 2.3.12)	
Bow Sonar Weight	Bow Sonar	4.2.1.2	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp56 Section 2.3.12)	
Flank Array Sonar	Flank Array Sonar	4.2.2				
Flank Array Sonar Length	Flank Array Sonar	4.2.2.1	Y	N	Assumed Approximately 20% of LOA	20%
Flank Array Sonar Width	Flank Array Sonar	4.2.2.2	N	Y	Used data in UCL Submarine Design Databook 2012 (pp60 Section 2.3.15)	
Flank Array Sonar Weight	Flank Array Sonar	4.2.2.3	N	Y	Used data in UCL Submarine Design Databook 2012 (pp60 Section 2.3.15)	
Flank Array Sonar Volume	Flank Array Sonar	4.2.2.4	N	Y	Passive Ranging Sonar Hydrophones are relatively small and light and thus will not have significant impact on the geometric arrangement of the submarine	
Towed Array Sonar	Towed Array Sonar	4.2.3				
Towed Array Sonar Length	Towed Array Sonar	4.2.3.1	Y	N	Assumed to be 30m as suggested by UCL Submarine Design Databook 2012 (pp 58 Section 2.3.14)	30 m
Towed Array Sonar Sizing	Towed Array Sonar	4.2.3.2	N	Y	Used Equations in UCL Submarine Design Databook 2012 (pp 58 Section 2.3.14)	
Towed Array Sonar Weight	Towed Array Sonar	4.2.3.3	N	Y	Used Equations for Options in UCL Submarine Design Databook 2012 (pp 58 Section 2.3.14)	
Passive Bearing Sonar	Bow Sonar	4.2.4				
Passive Bearing Sonar Cost and Capability	Bow Sonar	4.2.4.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Passive Ranging Sonar	Flank Array Sonar	4.2.5				
Passive Ranging Sonar Cost and Capability	Flank Array Sonar	4.2.5.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Passive Class Active Bearing Sonar	Towed Array Sonar	4.2.6				
Passive Class Active Bearing Sonar Cost and Capability	Towed Array Sonar	4.2.6.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Radar Mast	Radar Mast	4.2.7				
Radar Mast Cost and Capability	Radar Mast	4.2.7.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp31 Section 2.2.3)	
Optronic Mast	Optronic Mast	4.2.8				
Optronic Mast Cost and Capability	Optronic Mast	4.2.8.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp 33 Section 2.2.4)	
Optronic Mast Options	Optronic Mast	4.2.8.2	N	Y	ESM Optronic Mast Options 3&4 in UCL Submarine Design Databook 2012 (pp 33 Section 2.2.4) are Attack Optronic Masts, all other options have only Search Optronic masts.	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Optronic Mast Cost of Non-Penetration of PH	Optronic Mast	4.2.8.3	Y	N	Assumed all masts are non-penetrating – this results in 10x cost (vs. traditional mast), as advised by Submarine Design Databook 2012 (pp 33 Section 2.2.4)	
Communications	Comms. Mast	4.2.9				
Communications Cost and Capability	Comms. Mast	4.2.9.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp35 Section 2.2.5)	
Communications Cryptography	Comms. Mast	4.2.9.2	Y	N	Assumed 2x cost as high specification cryptography is seen to be required (as indicated in UCL Submarine Design Databook 2012) (pp34 Section 2.2.5)	
Communications Composition	Comms. Mast	4.2.9.3	N	Y	Some comms options in UCL Submarine Design Databook 2012 (pp34 Section 2.2.5) specify towed buoys as well as a comms mast	
Communications Masts	Comms. Mast	4.2.9.4	Y	N	Assumed 2x comms masts as comms are considered mission critical to command UUV fleet (as indicated by Submarine Design Databook 2012 (pp35 Section 2.2.5))	
Mast Weight	Payload Masts	4.2.9.5	Y	N	Assumed 1.5 Tonnes	1.5 Tonnes
Command Compartments		4.3				
C2 Room	C2 Room	4.3.1				
Combat Management System	C2 Room	4.3.1.1				
Combat Management System Cost and Capability	C2 Room	4.3.1.1.1	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp 36 Section 2.2.6)	
Combat Management System Console, CPU and complement Numbers	C2 Room	4.3.1.1.2	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp 36 Section 2.2.6)	
Combat Management System Development Cost	C2 Room	4.3.1.1.3	Y	N	Assume an extra 20% for potential development cost overrun for new systems, as advised by Submarine Design Databook 2012 (pp 36 Section 2.2.6)	
C2 Room Consoles	C2 Room	4.3.1.2				
CPU to Cabinet Ratio	C2 Room	4.3.1.2.1	Y	N	Assumed 6 CPU / Cabinet as advised by Submarine Design Databook 2012 (pp 55 Section 2.3.11.1)	6 CPU / Cabinet
CPU Number for SNAPS	C2 Room	4.3.1.2.2	Y	N	Assumed 1 CPU	1 CPU
CPU Number for SINS	C2 Room	4.3.1.2.3	Y	N	Assumed 3 CPU	3 CPU
CPU Number for Trim and Comp	C2 Room	4.3.1.2.4	Y	N	Assumed 2 CPU	2 CPU
CPU Number for Infrastructure and Propulsion Functions	C2 Room	4.3.1.2.5	Y	N	Assumed 6 CPU	6 CPU
CPU Numbers for Passive Bearing Sonar	C2 Room	4.3.1.2.6	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
CPU Numbers for Passive Ranging Sonar	C2 Room	4.3.1.2.7	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
CPU Numbers for Passive Class Active Bearing Sonar	C2 Room	4.3.1.2.8	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
CPU Numbers for Radar Mast	C2 Room	4.3.1.2.9	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp31 Section 2.2.3)	
CPU Numbers for Optronic Mast	C2 Room	4.3.1.2.10	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp33 Section 2.2.4)	
Cabinet Height	C2 Room	4.3.1.2.11	N	Y	Taken to be 1.5m high. Submarine Design Databook (pp55 Section 2.3.11.1)	1.5m

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Cabinet Width and Depth	C2 Room	4.3.1.2.12	Y	N	Assumed 1m width and 1m Deep Submarine Design Databook (pp55 Section 2.3.11.1), plus 0.4m in both directions for access	0.4m
Cabinet Weight	C2 Room	4.3.1.2.13	N	Y	Taken as 0.15 Tonnes Submarine Design Databook (pp55 Section 2.3.11.1)	0.15 tonnes
Cabinet Water Cooling	C2 Room	4.3.1.2.14	N	Y	Taken as 1kW/Cabinet of Cooling Submarine Design Databook (pp55 Section 2.3.11.1)	1kW/Cabinet
Cabinet Weight	C2 Room	4.3.1.2.15	N	Y	Taken as 2kW/Cabinet Electrical Load Submarine Design Databook (pp55 Section 2.3.11.1)	2kW/Cabinet
C2 Room Consoles	C2 Room	4.3.1.2				
Console Number for SNAPS	C2 Room	4.3.1.2.1	Y	N	Assumed 1 Console	1 Console
Console Number for SINS	C2 Room	4.3.1.2.2	Y	N	Assumed 1 Console	1 Console
Console Number for Trim and Comp	C2 Room	4.3.1.2.3	Y	N	Assumed 2 Console	2 Consoles
Console Number for Infrastructure and Propulsion Functions	C2 Room	4.3.1.2.4	Y	N	Assumed 4 Consoles	4 Consoles
Console Numbers for Passive Bearing Sonar	C2 Room	4.3.1.2.5	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Console Numbers for Passive Ranging Sonar	C2 Room	4.3.1.2.6	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Console Numbers for Passive Class Active Bearing Sonar	C2 Room	4.3.1.2.7	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Console Numbers for Radar Mast	C2 Room	4.3.1.2.8	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp31 Section 2.2.3)	
Console Numbers for Optronic Mast	C2 Room	4.3.1.2.9	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp33 Section 2.2.4)	
Console Height	C2 Room	4.3.1.2.10	N	Y	Taken as to be 1.9m high. Submarine Design Databook (pp54 Section 2.3.10)	1.9m
Console Width and Depth	C2 Room	4.3.1.2.11	Y	N	Assumed 0.6m width and 1.6m Deep, plus 1m for chair + person and access	1m
Console Weight	C2 Room	4.3.1.2.12	N	Y	Taken as 0.2 Tonnes Submarine Design Databook (pp54 Section 2.3.10). Submarine Design Databook (pp54 Section 2.3.10)	0.2 tonnes
Console Water Cooling	C2 Room	4.3.1.2.13	N	Y	Taken as 1kW/Console of Cooling. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
Console Weight	C2 Room	4.3.1.2.14	N	Y	Taken as 1kW/Console Electrical Load. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
C2 Room Complement	C2 Room	4.3.1.3				
C2 Room Manning Consoles	C2 Room	4.3.1.3.1	Y	N	Assumed 1 person/console plus two watch officers	1 person/console
Complement Numbers for Passive Bearing Sonar	C2 Room	4.3.1.3.2	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Complement Numbers for Passive Ranging Sonar	C2 Room	4.3.1.3.3	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Complement Numbers for Passive Class Active Bearing Sonar	C2 Room	4.3.1.3.4	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp30 Section 2.2.2)	
Complement Numbers for Radar Mast	C2 Room	4.3.1.3.5	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp31 Section 2.2.3)	
Complement Numbers for Optronic Mast	C2 Room	4.3.1.3.6	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp33 Section 2.2.4)	
Person Weight	C2 Room	4.3.1.3.7	Y	N	Assumed average weight of person is 75 kg	75 kg

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Furniture	C2 Room	4.3.1.4	Y	N	Assumed average weight of furniture is 25 kg	25kg
Furniture Composition	C2 Room	4.3.1.4.1	Y	N	Assumed to encompass tables, chairs, bulkheads, etc.	
Furniture to Person Ratio	C2 Room	4.3.1.4.2	Y	N	Assumed One piece of Furniture per Person	1 to 1
Furniture Total Area	C2 Room	4.3.1.4.3	Y	N	Assumed 6 m^2	6 m^2
Furniture Total Volume	C2 Room	4.3.1.4.4	Y	N	Assumed 15 m^3	15 m^3
MCC Room	MCC Room	4.3.2				
CPU to Cabinet Ratio	MCC Room	4.3.2.1.1	Y	N	Assume 6 CPU / Cabinet as advised by Submarine Design Databook 2012 (pp 55 Section 2.3.11.1)	6 CPU / Cabinet
CPU Numbers for TLAM	MCC Room	4.3.2.1.2	Y	N	Assumed 6 CPUs if TLAM are part of payload	6 CPU
CPU Numbers for Cat. A MUV/UUVs	MCC Room	4.3.2.1.3	Y	N	Assumed 1 CPU per 2 Cat. A UUVs	1 CPU / Cat. A UUV
Cabinet Height	MCC Room	4.3.2.1.4	Y	N	Taken to be 1.5 m high. Submarine Design Databook (pp55 Section 2.3.11.1)	1.5 m
Cabinet Width and Depth	MCC Room	4.3.2.1.5	Y	N	Assume 1m width and 1m Deep Submarine Design Databook (pp55 Section 2.3.11.1), plus 0.4m in both directions for access	0.4 m
Cabinet Weight	MCC Room	4.3.2.1.6	Y	N	Taken as 0.15 Tonnes Submarine Design Databook (pp55 Section 2.3.11.1)	0.15 tonnes
Cabinet Water Cooling	MCC Room	4.3.2.1.7	Y	N	Taken as 1kW/Cabinet of Cooling Submarine Design Databook (pp55 Section 2.3.11.1)	1kW/Cabinet
Cabinet Weight	MCC Room	4.3.2.1.8	Y	N	Taken as 2kW/Cabinet Electrical Load Submarine Design Databook (pp55 Section 2.3.11.1)	2kW/Cabinet
Console Height	MCC Room	4.3.2.1.9	Y	N	Taken as to be 1.9m high. Submarine Design Databook (pp54 Section 2.3.10)	1.9 m
Console Width and Depth	MCC Room	4.3.2.1.10	Y	N	Assume 0.6m width and 1.6m Deep, plus 1m for chair + person and access	1 m
Console Weight	MCC Room	4.3.2.1.11	Y	N	Taken as 0.2 Tonnes Submarine Design Databook (pp54 Section 2.3.10). Submarine Design Databook (pp54 Section 2.3.10)	0.2 tonnes
Console Water Cooling	MCC Room	4.3.2.1.12	Y	N	Taken as 1kW/Console of Cooling. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
Console Weight	MCC Room	4.3.2.1.13	Y	N	Taken as 1kW/Console Electrical Load. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
MCC Room Complement	MCC Room	4.3.2.2				
MCC Room Manning Consoles	MCC Room	4.3.2.2.1	Y	N	Assumed 1 person/console plus two watch officers	
Complement Numbers for Cat A MUV/UUV Control	MCC Room	4.3.2.2.2	Y	N	Assumed due to the high level required of autonomy for Cat. A MUVs on station that as a result minimal mission control is required. Assume 1 Person/6 Cat. A MUVs	1 Person/6 Cat. A MUVs
Complement Numbers for Cat. B and C Control	MCC Room	4.3.2.2.3	Y	N	Assumed that Control of Cat. B and C UUVs are undertaken locally by Cat. A Hub MUV/UUVs	
Complement Numbers for LA Control	MCC Room	4.3.2.2.4	Y	N	Assumed 1 Person for LA Mission Control	1 Person
Person Weight	MCC Room	4.3.2.2.5	Y	N	Assumed average weight of person is 75 kg	
Furniture	MCC Room	4.3.2.3	Y	N	Assumed average weight of furniture is 25 kg	75 kg
Furniture Composition	MCC Room	4.3.2.3.1	Y	N	Assumed to encompass tables, chairs, bulkheads, etc.	25 kg
Furniture to Person Ratio	MCC Room	4.3.2.3.2	Y	N	Assumed one piece of Furniture per Person	
Furniture Total Area	MCC Room	4.3.2.3.3	Y	N	Assumed 2 m^2	2 m^2
Furniture Total Volume	MCC Room	4.3.2.3.4	Y	N	Assumed 5 m^3	5 m^3

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Comms Room	Comms Room	4.3.3				
CPU to Cabinet Ratio	Comms Room	4.3.3.1.1	Y	N	Assumed 6 CPU / Cabinet as advised by UCL Submarine Design Databook 2012 (pp 55 Section 2.3.11.1)	
CPU Numbers for Comms	Comms Room	4.3.3.1.2	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp 35 Section 2.2.5)	
Cabinet Height	Comms Room	4.3.3.1.3	Y	N	Taken to be 1.5m high. UCL Submarine Design Databook 2012 (pp55 Section 2.3.11.1)	
Cabinet Width and Depth	Comms Room	4.3.3.1.4	Y	N	Assumed 1m width and 1m Deep UCL Submarine Design Databook 2012 (pp55 Section 2.3.11.1), plus 0.4m in both directions for access	
Cabinet Weight	Comms Room	4.3.3.1.5	Y	N	Taken as 0.15 Tonnes Submarine Design Databook (pp55 Section 2.3.11.1)	0.15 tonnes
Cabinet Water Cooling	Comms Room	4.3.3.1.6	Y	N	Taken as 1kW/Cabinet of Cooling UCL Submarine Design Databook 2012 (pp55 Section 2.3.11.1)	1kW/Cabinet
Cabinet Weight	Comms Room	4.3.3.1.7	Y	N	Taken as 2kW/Cabinet Electrical Load UCL Submarine Design Databook 2012 (pp55 Section 2.3.11.1)	2kW/Cabinet
Console Height	Comms Room	4.3.3.1.8	Y	N	Taken as to be 1.9 m high. UCL Submarine Design Databook 2012 (pp54 Section 2.3.10)	1.9 m
Console Width and Depth	Comms Room	4.3.3.1.9	Y	N	Assumed 0.6m width and 1.6m Deep, plus 1 m for chair + person and access	1 m
Console Weight	Comms Room	4.3.3.1.10	Y	N	Taken as 0.2 Tonnes Submarine Design Databook (pp54 Section 2.3.10). Submarine Design Databook (pp54 Section 2.3.10)	0.2 tonnes
Console Water Cooling	Comms Room	4.3.3.1.11	Y	N	Taken as 1kW/Console of Cooling. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
Console Weight	Comms Room	4.3.3.1.12	Y	N	Taken as 1kW/Console Electrical Load. Submarine Design Databook (pp54 Section 2.3.10)	1kW/Console
Comms Room Complement	Comms Room	4.3.3.2				
Comms Room Manning Consoles	Comms Room	4.3.3.2.1	Y	N	Assumed 1 person/console plus two watch officers	
Complement Numbers for Comms	Comms Room	4.3.3.2.2	N	Y	Used Specifications for Options in UCL Submarine Design Databook 2012 (pp 35 Section 2.2.5)	1 Person/6 Cat. A MUVs
Person Weight	Comms Room	4.3.3.2.3	Y	N	Assumed average weight of person is 75 kg	
Furniture	Comms Room	4.3.3.3	Y	N	Assumed average weight of furniture is 25 kg	
Furniture Composition	Comms Room	4.3.3.3.1	Y	N	Assumed to encompass tables, chairs, bulkheads, etc.	25 kg
Furniture to Person Ratio	Comms Room	4.3.3.3.2	Y	N	Assumed one piece of Furniture per Person	
Furniture Total Area	Comms Room	4.3.3.3.3	Y	N	Assumed 2 m^2	2 m^2
Furniture Total Volume	Comms Room	4.3.3.3.4	Y	N	Assumed 5 m^3	5 m^3
Weapons		4.4				
Torpedoes		4.4.1				
Torpedo Weapon	Torpedo Launch	4.4.1.1				
Torpedo Selection	Torpedo Launch	4.4.1.1.1	Y	N	Assumed to be Spearfish Torpedo	
Torpedo Sizing	Torpedo Stow	4.4.1.1.2	N	Y	Used Specifications for Spearfish in UCL Submarine Design Databook 2012 (pp40 Section 2.3.2.3)	
Torpedo Weight	Torpedo Stow	4.4.1.1.3	N	Y	Used Specifications for Spearfish in UCL Submarine Design Databook 2012 (pp40 Section 2.3.2.3)	

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Torpedo Stowed and Launch		4.4.1.2				
Torpedo Handling Equipment Weight	Torpedo Stow	4.4.1.2.1	N	Y	Used Specifications for Spearfish in UCL Submarine Design Databook 2012 (pp 38 Section 2.3.1) of 1.85 tonnes/weapons. N.B. This includes all weapons in the compartment including TLAM	1.85 tonnes/weapon
Torpedo External Stowed Volume	Torpedo Stow	4.4.1.2.2	Y	N	Assume a 20% Volume Penalty for externally stowed due to additional mounting/attachment to PH	20%
Torpedo Externally Stowed Configuration	Torpedo Stow	4.4.1.2.3	N	Y	External stowed can be in self-contained compartments for single-shot torpedoes or in a magazine curled around the PH for multiple-shot torpedoes. Assume both need to be pressurised Cylinders	20%
Torpedo Tube Diameter	Torpedo Launch	4.4.1.2.4	Y	N	Assumed to be standard 21"	21"
Torpedo Tube Sizing	Torpedo Launch	4.4.1.2.5	N	Y	Used Specifications for 21" tube in UCL Submarine Design Databook 2012 (pp 38 Section 2.3.1)	
Torpedo Tube Weight	Torpedo Launch	4.4.1.2.6	N	Y	Used Specifications for 21" tube in UCL Submarine Design Databook 2012 (pp 38 Section 2.3.1)	
ATP Number	Torpedo Launch	4.4.1.2.6	Y	N	Assumed 2 ATP – One for Starboard and One for Port Torpedo Tube Bank	2 Pumps
ATP Weight	Torpedo Launch	4.4.1.2.7	N	Y	Used Specifications for ATP in UCL Submarine Design Databook 2012 (pp 43 Section 2.3.4)	3.65 Tonnes/Pump
ATP Diameter	Torpedo Launch	4.4.1.2.8	Y	N	Assumed based on Submarine Design Databook 2012 (pp 43 Section 2.3.4) Information	1m
ATP System Weight	Torpedo Launch	4.4.1.2.9	N	Y	Used Specifications for ATP in UCL Submarine Design Databook 2012 (pp 43 Section 2.3.4)	1.7 Tonnes
Operating Fluid Weight	Torpedo Launch	4.4.1.2.10	N	Y	Used Specifications for ATP in UCL Submarine Design Databook 2012 (pp 43 Section 2.3.4)	500 kg / System
Discharged Air Weight	Torpedo Launch	4.4.1.2.11	N	Y	Used Specifications for ATP in UCL Submarine Design Databook 2012 (pp 43 Section 2.3.4)	14 kg/ Launch
Number of Torpedo Tube Banks	Torpedo Tube Bank	4.4.1.2.12	Y	N	Assumed one Port and one Starboard bank	2 Tube banks
Torpedo Tube Vertical Spacing	Torpedo Tube Bank	4.4.1.2.13	Y	N	Assumed 0.5 m spacing	0.5m
Torpedo Tube Bank Width	Torpedo Tube Bank	4.4.1.2.14	Y	N	Assumed maximum of ATP Diameter and 21" + 0.5m spacing	
Torpedo Tube Bank Arrangement	Torpedo Tube Bank	4.4.1.2.15	Y	N	Assumed each bank of tubes are arranged vertically in a single column	
Mines		4.4.2				
SLMM Selection	Torpedo Stow	4.4.2.1	Y	N	Assumed to be SLMM (As RN S/Ms no longer carry mines)	
SLMM Sizing	Torpedo Stow	4.4.2.1.1	N	Y	Used Specifications for SLMM in UCL Submarine Design Databook 2012 (pp 53 Section 2.3.9.1)	
SLMM Weight	Torpedo Stow	4.4.2.1.2	N	Y	Used Specifications for SLMM in UCL Submarine Design Databook 2012 (pp 53 Section 2.3.9.1)	
SLMM Cost	Torpedo Stow	4.4.2.1.3	Y	N	Assumed using the value in UCL Submarine Design Databook 2012 (pp 28 Section 2.2.1.1)	
SLMM Stow and Launch	Torpedo Stow	4.4.2.2	Y	N	Assumed to be stowed in WSC and torpedo tube launched.	
LAM		4.4.3				

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
LAM Selection	TLAM Stow	4.4.3.1	Y	N	Assume to be Tomahawk Land Attack Missile (TLAM)	
TLAM Sizing	TLAM Stow	4.4.3.1.1	N	Y	Used Specifications for TLAM in UCL Submarine Design Databook 2012 (pp49 Section 2.3.7.1)	
TLAM Weight	TLAM Stow	4.4.3.1.2	N	Y	Used Specifications for TLAM in UCL Submarine Design Databook 2012 (pp49 Section 2.3.7.1)	
LAM Stowed and Launch	TLAM Stow	4.4.3.2				
TLAM Stow and Launch Arrangement	TLAM Stow	4.4.3.2.1	Y	N	Assumed TLAMs are stored and launched from same compartment	
TLAM Stow VLS Selection	TLAM Stow	4.4.3.2.2	N	Y	Can be stowed in the WSC, in a single vertical launch tube, or a MAC canister containing 3 or 7 TLAMS	
TLAM Stow Options	TLAM Stow	4.4.3.2.3	Y	N	Assumed all VLS options (including MAC canister) use the USN's mk. 57 system. See Raytheon Literature “MK 57 Vertical Launching System (VLS)”	
VLS Weight	TLAM Stow	4.4.3.2.4	N	Y	Used specifications from Raytheon Literature “MK 57 Vertical Launching System (VLS)”	
VLS Sizing	TLAM Stow	4.4.3.2.5	N	Y	Used specifications from Raytheon Literature “MK 57 Vertical Launching System (VLS)”	
MAC (7 Missile) Sizing	TLAM Stow	4.4.3.2.6	N	Y	Used specifications from http://en.wikipedia.org/wiki/UGM-133_Trident_II (diameter of trident 11)	
MAC (7 Missile) Weight	TLAM Stow	4.4.3.2.7	Y	N	Calculated from SSGN ‘Hailstorm’ (UCL Submarine Design course 2011) report	38.8 Tonnes
MAC (3 Missile) Sizing	TLAM Stow	4.4.3.2.8	Y	N	Assume to scale linearly using the number of TLAM	
MAC (3 Missile) Weight	TLAM Stow	4.4.3.2.9	Y	N	Assume to scale linearly using the number of TLAM	
IDAS Missile		4.4.4				
IDAS Missile Weight	Triple-M Mast	4.4.4.1	Y	N	Used Specifications from http://www.diehl.com/fileadmin/diehl-defence/user_upload/flyer/IDAS_07_2008.pdf	
IDAS Missile Sizing	Triple-M Mast	4.4.4.2	Y	N	Used Specifications from http://www.diehl.com/fileadmin/diehl-defence/user_upload/flyer/IDAS_07_2008.pdf	
IDAS Missile Arrangement	Triple-M Mast	4.4.4.3	N	Y	Either a Single Missile House in Triple-M mast of multiple stowed in Weapons Stow Compartment. See en.wikipedia.org/wiki/IDAS_(missile)	
Muraena Gun		4.4.5				
Muraena Gun Weight	Triple-M Mast	4.4.5.1	Y	N	Assumed to be similar to http://en.wikipedia.org/wiki/Mauser_BK-27	
Muraena Gun Sizing	Triple-M Mast	4.4.5.2	Y	N	Assumed to be similar to http://en.wikipedia.org/wiki/Mauser_BK-27	
Muraena Gun Arrangement	Triple-M Mast	4.4.5.3	N	Y	Housed in Triple-M Mast	
Countermeasures		4.4.6				
Bandfish Selection	CM Stow	4.4.6.1	Y	N	Assumed to be Bandfish	
Bandfish Sizing	CM Stow	4.4.6.1.1	N	Y	Used Specifications for Bandfish in UCL Submarine Design Databook 2012 (pp 62 Section 2.3.17)	
Bandfish Weight	CM Stow	4.4.6.1.2	N	Y	Used Specifications for Bandfish in UCL Submarine Design Databook 2012 (pp 62 Section 2.3.17)	
Signal Ejector (SE) Weight	CM Stow	4.4.6.1.3	N	Y	Used Specifications for Bandfish in UCL Submarine Design Databook 2012 (pp 62 Section 2.3.17)	2 tonnes
Countermeasures (CM) Stow and Launch	CM Stow	4.4.6.2				

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Countermeasures (CM) Stow and Launch Arrangement	CM Stow	4.4.6.2.1	Y	N	Assume CMs are stored and launched from same compartment	
Number of CM Banks	CM Stow	4.4.6.2.2	Y	N	2 Banks of CM Stow and Launchers for redundancy.	2 Banks of CM Launchers
Number of SEs	CM Stow	4.4.6.2.3	Y	N	Assumed 1 SE per CM	1 CME/ CM
CM Stow Height	CM Stow	4.4.6.2.4	Y	N	Assumed to be the same as Length of Bandfish plus 0.5m	
CM Stow Length	CM Stow	4.4.6.2.5	Y	N	Assumed Bandfish arranged in a row for each CM bank plus 0.5m	
CM Stow Weight	CM Stow	4.4.6.2.6	Y	N	Combined Weight of Bandfish and SEs for each CM bank. Assumed to always be stored wet.	
Crew		5				
Manning Composition		5.1				
Watch Officers		5.1.1				
Number of Captain	C2 Room	5.1.1.1	Y	N	Assumed to be 1 Captain	1 Person
Number of Executive Officers	C2 Room	5.1.1.2	Y	N	Assumed to be 1 Executive Officer	1 Person
Number of Navigation Officers	C2 Room	5.1.1.3	Y	N	Assumed to be 1 Navigation Officer	1 Person
Number of Watch Leaders	C2 Room	5.1.1.4	Y	N	Assumed to be 1 Warrant Officer	1 Person
Number of Warrant Officers	C2 Room	5.1.1.5	Y	N	Assumed to be 2 Watch Leaders	2 People
Number of Petty Officers	C2 Room	5.1.1.6	Y	N	Assumed to be 1 Petty Officer	1 Person
Number of Communications Officers	Comms Room	5.1.1.7	Y	N	Assumed to be 1 Communications Officer	1 Person
Number of Chief Petty Officers	C2 Room	5.1.1.8	Y	N	Assumed to be 1 Chief Petty Office / (Watch without a Watch Leader)	1 Person / Watch
Number of Watches		5.1.1.9	Y	N	Adopt assumption from UCL Submarine Design Databook 2012 (pp 139 Section 7.1) Indicates that 3-Watch System may be obtained by factoring 2-Watch data.	
Weapons Engineering		5.1.2				
Engineering Officers		5.1.2.1				
Number of Weapons Officers	Torpedo and UUV Stow and Launch Compartment	5.1.2.1.1	Y	N	Assumed to be 1 Weapons Officer	1 Person
Number of Deputy Weapons Officers	Torpedo and UUV Stow and Launch Compartment	5.1.2.1.2	Y	N	Assumed to be 1 Deputy Officer / (Watch without Weapons Officer)	1 Person / Watch
Traditional Payload		5.1.2.2				
Number of Comms and Info Officer (CISE)	Comms Room	5.1.2.2.1	Y	N	Assumed to be 1 CISE Officer per watch	1 Person / Watch
Number of Technicians for Traditional Weapons	Torpedo Stow and Torpedo Launch	5.1.2.2.2	Y	N	Assumed (Per watch) 1 Technician for ARM of Weapons and 1 Technician for the launch systems	2 Person / Watch
UUV Payload		5.1.2.3				
Number of Comms and Info Officer (CISE)	Comms Room	5.1.2.3.1	Y	N	Assumed to be 1 CISE Officer per watch. Assume another CISE officer needed for Cat A and Cat B&C UUV payloads due to the novelty of UUVs	1 Person / Watch

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Number of Technicians for Cat. A UUVs	Cat A. Stow and Cat. A LARS	5.1.2.3.2	Y	N	Assumed (Per watch) 1 Person per 4 UUVs plus 1 for LARS due to it being a complicated system	
Number of Technicians for Cat. B and C UUVs	Cat. B and C Stow and Cat. B and C LARS	5.1.2.3.3	Y	N	Assumed (Per Watch) 1 Person per 20 UUVs plus 1 for LARS due to it being a complicated system	
Mechanical and Electrical Engineering		5.1.3				
Number of Marine Engineering Officers	Propulsion Compartments	5.1.3.1	Y	N	Assumed to be 1 Marine Engineering Officer and 1 Deputy Officer	1 Marine Engineering Officer
Number of Marine Engineering Personnel	Propulsion Compartments	5.1.3.2	Y	N	Assumed based on equation from UCL Submarine Design Databook 2012 (pp 139 Section 7.1). Equation updated for improved modern ARM to be 1 man/700 tonnes and 1 man/engine. Engines including nuclear reactors.	
Logistics		5.1.4				
Number of Logistics Officers	Storage Compartments	5.1.4.1	Y	N	Assumed to be 1 Logistics Officer	1 Person
Number of Logisticians	Storage Compartments	5.1.4.3	Y	N	Assumed 2 Logisticians/ Watch	2 People / watch
Misc.		5.1.5				
Number of Special Forces/ Cat. A MUV Pilots	MCC Room	5.1.5.1	Y	N	Assume 1 SF or Pilot / Cat. A MUV	1 Person /Cat. A MUV/UUV
Number of Trainees	C2 Room	5.1.5.2	Y	N	Assume 1 Trainee/Watch	1 Person / watch
Number of Chief	Galley	5.1.5.3	Y	N	Assumed 1 Chief/ Watch	1 Person / watch
Manning Composition		5.1.6	N	Y	Composition of Officers, Senior Rates and Junior Rates based on that given in Submarine Design Databook 2012 (pp 139 Section 7.1)	
Accommodation		5.2				
Area of Accommodation Compartments	Accommodation Compartments	5.2.1	N	Y	Equations from the UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Length of Accommodation Compartments	Accommodation Compartments	5.2.2	N	Y	Equations from the UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Width of Accommodation Compartments	Accommodation Compartments	5.2.3	N	Y	Equations from the UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Volume of Accommodation Compartments	Accommodation Compartments	5.2.4	N	Y	Equations from the UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Weight of Accommodation Compartments	Accommodation Compartments	5.2.5	N	Y	Equations from the UCL Ship Design Databook 2012 , Based on Type 45 (pp 349 Section 18.1.1)	
Number of Accommodation Compartments	Accommodation Compartments	5.2.6	N	Y	Equations from the UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Stores		5.3				
Cold Room	Storage Compartments	5.3.1				
Cold Room Weight	Storage Compartments	5.3.1.1	Y	N	Assumed weight equation in UCL Ship Design Databook 2012 (pp 44 Section 3.2.3). Assumed 4.46 kg/man/patrol day	4.46 kg/man/patrol day

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Cold Room Sizing	Storage Compartments	5.3.1.2	Y	N	Assume tank wall have negligible thickness. Assumed 0.009 m^3/man/day UCL Submarine Design Databook 2012 (pp140 Section 7.2)	0.009 m^3/man/day
Fresh Water	Storage Compartments	5.3.2				
Fresh Water Weight	Storage Compartments	5.3.2.1	Y	N	Assumed enough water for 1 day for crew and feed consumption as taken from ship design Databook 2011 (pp107 Section 4.4)	
Fresh Water Sizing	Storage Compartments	5.3.2.2	Y	N	Assumed pure water (i.e. density of 1). Assume tank wall have negligible weight/thickness	
Pantry	Storage Compartments	5.3.3				
Pantry Weight	Storage Compartments	5.3.3.1	Y	N	Assumed equation taken from UCL Ship Design Databook 2012 (pp 46 Section 3.2.3). Assumed 1.6 kg/man/patrol day	1.6 kg/man/patrol day
Pantry Sizing	Storage Compartments	5.3.3.2	Y	N	Equation derived from UCL Submarine Design Databook 2012 (pp 140 Section 7.2).	
Communal Kit	Storage Compartments	5.3.4				
Communal Kit Weight	Storage Compartments	5.3.4.1	Y	N	Assumed Naval stores (25tonnes) + spare Gear (10 tonnes) from 'Hailstorm' SSGN (Submarine Design Course 2011)+Scaled General Finishes Scaled by Displacement Relative to 'Hailstorm' SSBN (Submarine Design Course 2011)	35 tonnes
Communal Kit Sizing	Storage Compartments	5.3.4.2	Y	N	Taken from UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Personal Kit	Storage Compartments	5.3.5				
Personal Storage Weight	Storage Compartments	5.3.5.1	Y	N	Assumed from UCL Ship Design Databook 2011 (pp47 Section 3.2.4) as 0.143 tonnes/man	0.146 tonnes/man
Personal Storage Sizing	Storage Compartments	5.3.5.2	Y	N	Taken from UCL Submarine Design Databook 2012 (pp 140 Section 7.2)	
Miscellaneous Outfit		5.4				
Fire-Fighting System Weight	Distributed	5.4.1	Y	N	Assume Scaled Linearly Relative to Displacement of SSGN 'Hailstorm' (UCL Submarine Design Course 2011)	
Mooring, Anchoring and Towing Combined Equipment Weight	Distributed	5.4.2	Y	N	Assume Scaled Linearly Relative to Displacement of SSGN 'Hailstorm' (UCL Submarine Design Course 2011)	
Lifting and Loading Combined System Weight	Distributed	5.4.3	Y	N	Assume Scaled Linearly Relative to Displacement of SSGN 'Hailstorm' (UCL Submarine Design Course 2011)	
Escape Equipment		5.5				
CO2 Absorption Unit Weight	Escape Towers	5.5.1	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.6)	
CO2 Absorption Unit Dimensions	Escape Towers	5.5.2	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.6)	
O2 Generation Unit Weight	Escape Towers	5.5.3	N	Y	Data from UCL Submarine Design Databook 2012 (pp135 Section 6.3.7)	
O2 Generation Unit Dimensions	Escape Towers	5.5.4	N	Y	Data from UCL Submarine Design Databook 2012 (pp134 Section 6.3.7)	
Life Saving Equipment Weight	Escape Towers	5.5.5	Y	N	Assumed to be 2 tonnes	2 Tonnes
CO2 and O2 Candles Weight	Escape Towers	5.5.6	N	Y	Equation taken from UCL Submarine Design Databook 2012 (pp 135 Section 6.3.3)	
Ballast		6				

Location	Object(s) in Question	Code Number	Assumption?	Note?	Description	Value (if applicable)
Permanent Ballast		6.1				
Ballast Composition	Permanent Ballast	6.1.1	N	Y	Ballast is composed of lead	
Ballast Density	Permanent Ballast	6.1.2	N	Y	Density of lead taken as 11.34 Tonnes/m^3	11.34 Tonnes/m^3

APPENDIX G - ACOUSTIC SIGNATURE MODEL

NOMENCLATURE

API:	Emitted Acoustic Power Intensity [W/m^2]
API_{Flow}	Emitted Acoustic Power Intensity from Flow around the Hull [W/m^2]
API_{Hotel}	Emitted Acoustic Power Intensity from Hotel Activities [W/m^2]
API_{Mach}	Emitted Acoustic Power Intensity from Propulsion Machinery inside the Hull [W/m^2]
API_{Prop}	Emitted Acoustic Power Intensity from the Interaction of the Propeller with Water [W/m^2]
API_{RC}	Emitted Acoustic Power Intensity from Nuclear Reactors [W/m^2]
$API_{re\ 1\ \mu Pa\ @1m}$	Emitted Acoustic Power Intensity Equal to a RMS Pressure of 1 µPa at 1 m [W/m^2]
CN	Cavitation Number
CN_{crit}	Critical Cavitation Number for Cavitation to take effect
$D_{50\%\ Sub}$	50% Probability Passive Acoustic Detection Range of a Submarine Design [nm]
$D_{50\%\ T\text{-}Class}$	50% Probability Passive Acoustic Detection Range of a Trafalgar Class [nm]
ELF –	Extremely Low Frequency
k_1	Collection of terms used in the description of SUPERB's Signature Model (In Appendix G)
N	Rotational Speed of the Propeller [revolutions/s]
p_{prop}	Water Pressure at the Propeller (At Hub)
Pr_{atm}	Atmospheric Pressure (Equal to is 101,325) [Pa]
Prop	Propeller (of a Submarine)
p_{vap}	Seawater Vapour (Relative) Pressure (Equal to at 981 @280 K) [Pa].
SL	Source Level (for submarine acoustics) [dB re 1µPa @1m]
T-Class	Trafalgar Class (UK) Submarine (SSN)
T_{water}	Temperature of Seawater [K]
Δh	Depth of Boat (From Keel) [m]
$\rho_{Seawater}$	Density of Seawater (Standard at 1.0275) [$Tonnes/m^3$]

G.1 INTRODUCTION

A model has been created by the candidate to quantify the broadband emitted acoustic power, in an effort to obtain some understanding into the signature of a submarine concept design generated by SUPERB. The model is outlined in this appendix.

The (broadband) acoustic noise emitted by a submarine has been assumed to comprise of four elements. The acoustic noise emitted from the vibration of propulsion machinery, the noise emitted by the flow of water around the submarine's hull ("hydrodynamic noise"), and noise from the spinning of the propulsor have been put forward by Tufano, et al (1996) as sources for noise. The noise from crew activities (termed here as "Hotel" noise) has also been addressed in this model.

G.2 HOTEL-BASED EMITTED ACOUSTIC POWER INTENSITY

This is the emitted acoustic power intensity from the crew and the supporting infrastructure equipment. This includes fans, pumps etc. as well general noise from the activities of the crew. It is assumed to be a function of manning numbers (which are in turn assumed proportional to the submarine's displacement).

This assumption is described mathematically by[1]:

$$API_{Hotel}=f\left(Num_{Manning}\right)=c_1 Num_{Manning}+c_2 \qquad \text{(Eqn. G1)}$$

It was assumed there would always be base level of sound emitted from a submarine, due to hotel loads independent of the level of manning. This would be in addition to the level of sound, which is assumed proportional to crew numbers.

G.3 PROPULSION MACHINERY NOISE-BASED EMITTED ACOUSTIC POWER INTENSITY

This is noise emitted from the propulsion machinery such as turbo-generators and turbines, as well as the primary energy generators (e.g. nuclear reactors). Miasnikov (1995) noted that some constant noise would come from machinery fans, pumps etc. He suggested an estimate for this constant emitted noise level to be 73 dB (the constant emitted noise power intensity is denoted as k_1). Furthermore, Miasnikov, (1995) suggested a 10 dB level should be allowed for nuclear power (API_{RC}) over SSKs on battery power at low speeds. Assuming that two reactors (Num_{Nuke}) would double the emitted power (i.e. an extra 3dB as the power scales linearly), an expression for the constant emitted noise from the machinery has been formed:

$$API_{Hotel}=f\left(Num_{Manning}\right)=c_1 Num_{Manning}+c_2 \qquad \text{(Eqn. G2)}$$

$$API_{RC}[dB]\approx 10\log_{10}(10Num_{Nuke}+1) \qquad \text{(Eqn. G3)}$$

Adding in the constant emitted power intensity from other machinery sources (the 73 dB), k_1 becomes:

$$k_1\ [dB]\approx 10\log_{10}(10Num_{Nuke}+1)+73 \qquad \text{(Eqn. G4)}$$

[1] c_1 and c_2 are constants which are stated later in this appendix

Figure A1.1 in Miasnikov (1995) indicated that log (relative sound level) is proportional to submarine speed. The constant of proportionality was indicated as approximately 30 dB / log (knot). Hence:

$$10\log_{10}\left(\frac{\mathrm{API_{Mach}}}{\mathrm{API_{re\ 1\mu PA\ @\ 1m}}}\right)[\mathrm{dB}]=30\left[\frac{\mathrm{dB}}{\log_{10}(\mathrm{knot})}\right]\times\log_{10}(\mathrm{v})+\mathrm{k_1} \qquad \text{(Eqn. G5)}$$

Which gives (substituting in for k_1):

$$10\log_{10}\left(\frac{\mathrm{API_{Mach}}}{\mathrm{API_{re\ 1\mu PA\ @\ 1m}}}\right)=30\log_{10}(\mathrm{v})+10\log_{10}(10\mathrm{Num_{Nuke}}+1)+73 \qquad \text{(Eqn. G6)}$$

Which simplifies to:

$$\left(\frac{\mathrm{AP_{Mach}}}{\mathrm{API_{re\ 1\mu PA\ @\ 1m}}}\right)=10^{7.3}\mathrm{v}^3(10\mathrm{Num_{Nuke}}+1) \qquad \text{(Eqn. G7)}$$

Rearranging, this becomes:

$$\mathrm{API_{Mach}}=10^{7.3}\mathrm{API_{re\ 1\mu PA\ @\ 1m}}\mathrm{v}^3(10\mathrm{Num_{Nuke}}+1) \qquad \text{(Eqn. G8)}$$

Tufano, et al (1996) constructed an equation for emitted machinery sound, which assumed a linear mechanical transmission system, and this has been adopted for the propulsion machinery noise. It has been assumed that this linearity remains valid for any boat velocity (i.e. any speed of drive shaft). Miasnikov (1995) indicated that while machinery noise remains present, it becomes dominated by flow noise above approximately 8 knots.

G.4 FLOW NOISE-BASED EMITTED ACOUSTIC POWER INTENSITY

This is the emitted acoustic power intensity due to the flow of water around the casing of the boat. A certain percentage of the power required to overcome the resistance of the hull (R) as the boat travels (submerged) through the water, is converted to emitted acoustic power. The remaining proportion of this power is converted to other energy types such as the kinetic energy in the swirl of an eddy. Misanikov (1995) stated:

"The flow noise strongly depends on the submarine's speed, and generally the SL[1] [Source Level] is proportional to the speed raised to the sixth power."

[1] Measured at 1 m from a point source relative to a sound intensity of 1 μPa

Which gives a mathematical model for acoustic power intensity attributed the effects of flow (k2 is a constant of proportionality)[1].

$$API_{Flow}=k_2v^6 \qquad \text{(Eqn. G9)}$$

Thus, it was assumed that k_2 is proportional to a fraction (c_3) of the hull resistance for a given velocity, which is based on the submarine's hull shape coefficient (Kp) and total volume (V_{form}) (see Burcher & Rydill (1994))

$$k_2=c_3(kp\ V_{form}) \qquad \text{(Eqn. G10)}$$

Hence, the API for hydrodynamic flow is modelled thusly:

$$API_{Flow}=f(Kp,v,V_{form})=c_3(kp\ V_{form}\ v^6) \qquad \text{(Eqn. G11)}$$

This assumption has been implied by Miasnikov (1995) to be valid. Miasnikov (1995) provided data for a given submarine (a 1980's IKL design for a Type 209 SSK), which relates the emitted acoustic intensity level to speed by:

$$10\log_{10}\left(\frac{API_{Flow}}{API_{re\ 1\mu PA\ @\ 1m}}\right)=k_2\log_{10}(v)+k_3 \qquad \text{(Eqn. G12)}$$

Where k_3 represents a constant emitted noise due to flow, expressed in decibels. k_4 is the value of k_3 expressed as an absolute value for power intensity. Hence, k_3 is related to k_4:

$$k_3=10\log_{10}\left(\frac{k_4}{API_{re\ 1\mu PA\ @\ 1m}}\right) \qquad \text{(Eqn. G13)}$$

Substituting for k_3 to Eqn. G12 leaves:

$$10\log_{10}\left(\frac{API_{Flow}}{API_{re\ 1\mu PA\ @\ 1m}}\right)=k_2\log_{10}(v)+10\log_{10}\left(\frac{k_4}{API_{re\ 1\mu PA\ @\ 1m}}\right) \qquad \text{(Eqn. G14)}$$

Which reduces to:

$$\log_{10}\left(\frac{API_{Flow}}{API_{re\ 1\mu PA\ @\ 1m}}\right)=\log_{10}\left(v^{\frac{k_2}{10}}\frac{k_4}{API_{re\ 1\mu PA\ @\ 1m}}\right) \qquad \text{(Eqn. G15)}$$

[1] The speed of the boat is denoted by 'v'

So recalling Eqn. G11 gives:

$$API_{Flow}=v^{\frac{k_2}{10}}k_4=c_3(kp\ V_{form}\ v^6) \qquad \text{(Eqn. G16)}$$

Which gives values for the constants as:

$$k_2=60 \ \text{ and } k_4=c_3(kp\ V_{form})$$

G.5 PROPULSION NOISE-BASED ACOUSTIC POWER INTENSITY

This is the acoustic noise emitted by the propeller. It should be reiterated that only broadband noise is addressed in these models and not the discrete noise emitted by the propeller at predominantly low frequencies (typically 1-10 Hz (Miasnikov, 1995)). These discrete frequencies are caused by thrust vibration noise, as discussed and simulated by Wei, et al. (2012) and Andersen et al (2009). To identify these discrete frequencies a propeller must be modelled in detail – which has been considered outside the scope of an early concept submarine design by the candidate.

The broadband noises (typically 100 Hz to 1000 Hz) according to Andersen, et al. (2009) are predominately from turbulence in the inflow to the propeller. The open water efficiency is dependent on the ratio of inflow water velocity (which is proportional to boat velocity) to the linear velocity of the tips on the propeller blades. It has been assumed that for the range of boat velocities of interest (0 to ~ 40 knots), that rotational speed of the propeller (N) is proportional to the boat's velocity and hence the open water efficiency of the propulsor remains constant.

It has also been assumed that the acoustic sound is a function of the speed of the boat (v), which in turn is related to R, the propeller's propulsive efficiency coefficient (PC) and transmission efficiency (η_s). The transmission efficiency was assumed to be 98%. Assuming that emitted acoustic power is proportional to the propulsive efficiency of the propeller, an expression for the emitted acoustic power intensity due to the propeller has been formed:

$$API_{Prop}=c_4\ PC\ R=c_4\ PC\ /\eta_s(kp\ V_{form}\ v^{2.9}) \qquad \text{(Eqn. G17)}$$

The boat velocity at which cavitation takes effect on the emitted acoustic noise has also been addressed. Cavitation reduces the propeller's efficiency and increases the emitted acoustic noise. The cavitation number (CN) is a function of the wake fraction (w_t), the boat velocity (v), water temperature (T_{water}) and pressure at boat propeller depth (p_{prop}) (atljsoft.com, 2010).

The equation given (atljsoft.com, 2010) for CN is:

$$CN=\frac{(p_{atm}+p_{prop}-p_{vap})}{0.5\rho_{seawater}v_a^2} \qquad \text{(Eqn. G18)}$$

Assuming the water temperature is 280 degrees Kelvin and the boat is at periscope depth (typically 10m) – the cavitation number (CN) is found with the following process:

Flow into propeller (v_a), according to Burcher and Rydill (1994) is:

$$v_a=(1-w_t)v \qquad \text{(Eqn. G19)}$$

The seawater vapour pressure (p_{vap}) at (280 K) is 981 Pa and atmospheric pressure (p_{atm}) is 101,325 Pa. The density of seawater[1] at 280 K is 1.0275 tonne/m^3.

Water pressure at the propeller (p_{prop}) is thus:

$$p_{prop}=\rho_{seawater}g\Delta h=1027.5\times9.81\times10=100{,}798 \text{ Pa} \qquad \text{(Eqn. G20)}$$

So, the CN at 10m depth is calculated:

$$CN=\frac{(101325+100798-981)}{0.5\times1027.5\times(1-w_t)^2v^2}=\frac{201{,}142}{513.75\times(1-w_t)^2v^2} \qquad \text{(Eqn. G21)}$$

Converting from velocity expressed in m/s to knots:

$$CN=\frac{201{,}142}{513.75\ (1-w_t)^2 0.514^2v^2}=\frac{201{,}142}{135.7\ (1-w_t)^2v^2} \qquad \text{(Eqn. G22)}$$

Figure A1.1 in Miasnikov (1995) gave the speed of a typical submarine required for cavitation to take effect as 22 knots. Assuming a typical wake fraction of 0.3, an assumed typical critical CN (CN_{crit}) can be estimated:

$$CN_{crit}=\frac{201{,}142}{135.7\ (1-0.3)^2\ 22^2}\approx 6.25 \qquad \text{(Eqn. G23)}$$

[1] Taken from the International Towing Tank Conference (IITC) (2011)

Figure A1.1 in Miasnikov (1995) also indicated that an increase in emitted noise of about 7dB would be expected due the onset of cavitation, i.e. at the point the calculated CN is equal to CN_{crit}. This is expressed mathematically as:

$$CN \leq CN_{crit}\,,\ \ AP_{Prop}=10^{0.8}c_4\ PC/\ \eta_s(kp\ V_{form}\ v^{2.9}) \qquad \text{(Eqn. G24)}$$
$$CN > CN_{crit}\,,\ \ AP_{Prop}=c_4\ PC/\ \eta_s(kp\ V_{form}\ v^{2.9})$$

G.6 TOTAL EMITTED ACOUSTIC POWER INTENSITY

Summing all the emitted acoustic power intensity source together gives:

$$API=API_{Hotel}+API_{Mach}+API_{Flow}+API_{Prop} \qquad \text{(Eqn. G25)}$$

If $CN>CN_{crit}$:

$$API=c_1 Num_{Manning}+c_2+API_{re\ 1\mu PA\ @\ 1m}\ v^3(10Num_{Nuke}+1)*\ 10^{7.3}+c_3(kp\ V_{form}\ v^6)$$
$$+10^{0.8}c_4\ PC\ /\eta_s(kp\ V_{form}\ v^{2.9}) \qquad \text{(Eqn. G26)}$$
$$API=c_1 Num_{Manning}+c_2+API_{re\ 1\mu PA\ @\ 1m}\ v^3(10Num_{Nuke}+1)*\ 10^{7.3}$$
$$+\left(kp\ V_{form}\ v^{2.9}\right)\left((c_3\ v^{3.1})+c_4\ PC/\ \eta_s\right)$$

If $CN \leq CN_{crit}$:

$$API=c_1 Num_{Manning}+c_2+API_{re\ 1\mu PA\ @\ 1m}\ v^3(10Num_{Nuke}+1)*\ 10^{7.3}+c_3(kp*V_{form}*v^6)$$
$$+10^{0.8}c_4\ PC/\ \eta_s(kp*V_{form}*v^{2.9}) \qquad \text{(Eqn. G27)}$$
$$API=c_1 Num_{Manning}+c_2+API_{re\ 1\mu PA\ @\ 1m}\ v^3(10Num_{Nuke}+1)*\ 10^{7.3}+\left(kp*V_{form}*v^{2.9}\right)$$
$$\left((c_3*v^{3.1})+10^{0.8}c_4\ PC/\ \eta_s\right)$$

It should be noted that all the constants must be real and non-negative, to ensure that the value for API is both non-imaginary and non-negative. This is because API is a real physical quantity and the mathematical model must reflect this. Using (Miasnikov, 1995) as a source for values of API, in conjunction with SUPERB's submarine modelling and other sources, the following table has been produced:

Table G1 – Data of Real Submarines Used to Find Values for the Constants[1]

Submarine	Delta III (USSR)	Akula I (USSR)	Typhoon (USSR)	Type 209 (GER)
Source Level @100$_{Hz}$ [dB re 1μPa @1m]	130	110	125	117
API $_{@100Hz}$ [μW]	6.488	0.065	2.052	0.325
V [knots]	4	6 (estimated)	6	8
Num $_{Manning}$	130	73	160	36
Kp	28.12	26.45	23.51	21.55
w_t	0.359	0.36	0.5	0.364
PC	0.7	0.91	0.74	0.94
Num$_{Nuke}$	2	1	2	0
V$_{form}$ [Tonnes]	17260	15600	68389	2648

Using a solver in MATLAB (using the "fminimax "function and ensuring no constants are negative) to solve the four simultaneous equations to find the values for the constants:

$$c_1=3.3099\times10^{-17};\ c_2=3.2747\times10^{-17};\ c_3=9.1547\times10^{-20};\ c_4=3.1567\times10^{-16}$$

G.7 FREQUENCY RELATIONSHIP

Based on Figure A1.2 in Miasnikov (1995), a reduction of signatures of 20 dB per decade in the frequency domain has been assumed. In this figure, the graph lines continue up to 30 Hz where it is expected that discrete frequencies produce the highest levels of emitted sound. This source also indicated that emitted sound from these discrete frequencies are about 20 dB higher and one decade lower than the break point (i.e. the point at which discrete frequencies no longer dominate the emitted sound). The corollary is that the trend of emitted sound declining by 20 dB/decade can simply be extended to the 1-10 Hz range of frequencies that are of interest.

G.8 EXAMPLE

The 8900 tonne French SSBN *Le Redoutable* interpreted by SUPERB (see Appendix H Section H.3); the emitted acoustic power intensity as a function of boat velocity and frequency has been calculated using the model described in this appendix.

[1] Sources for Table G1 (Military-Today.com, 2007a) (Military-Today.com, 2007b) (Military-Today.com, 2014a) (Military-Today.com, 2014b)

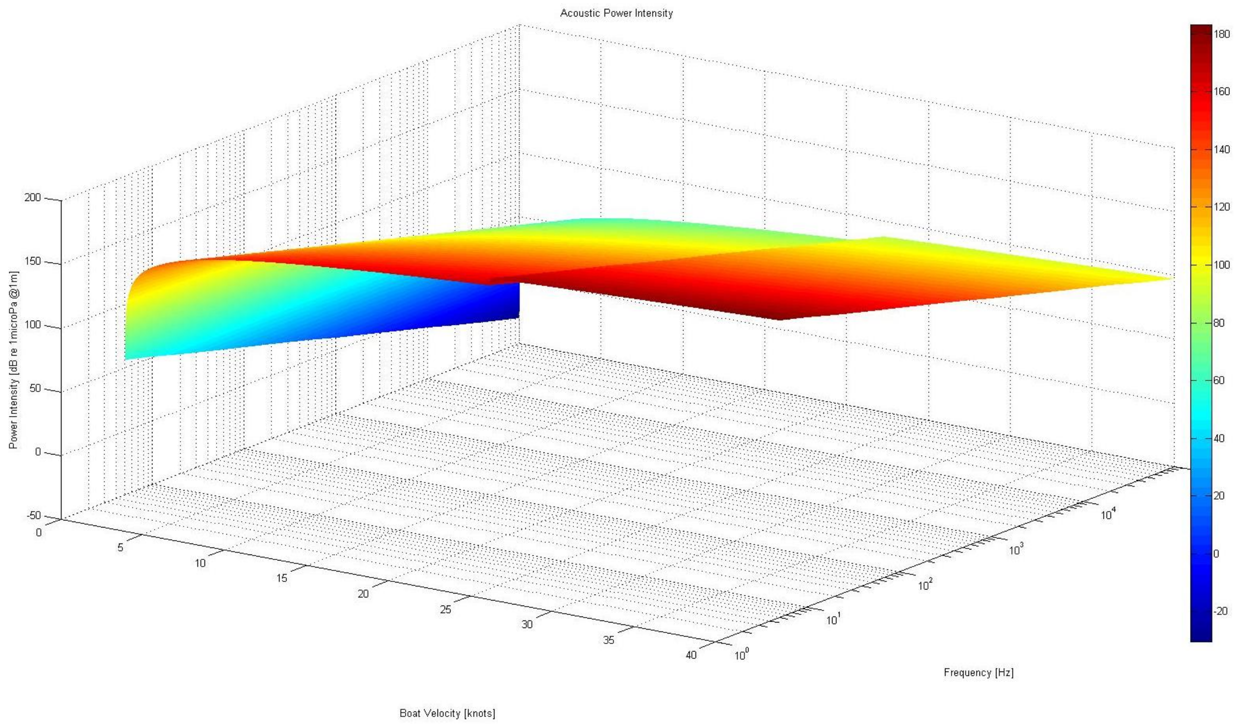

Figure G1 – The Acoustic Power Intensity for an Example 8900 tonne SSBN as Calculated by the Model

Figure G1 shows the model reflecting the effects of cavitation, which ‘steps’ up the API. The effects of increasing velocity between approximately 0 and 8 knots are predicted by the model to be significant. Furthermore, the model reflects that the most powerful emitted acoustic (broadband) noise is found at the low end of the spectrum.

APPENDIX H - SUPERB-GENERATED SUBMARINE DESIGNS

H.1 UCL 5,000 TONNE SSN

H.1.1 THREE-DIMENSIONAL VIEW

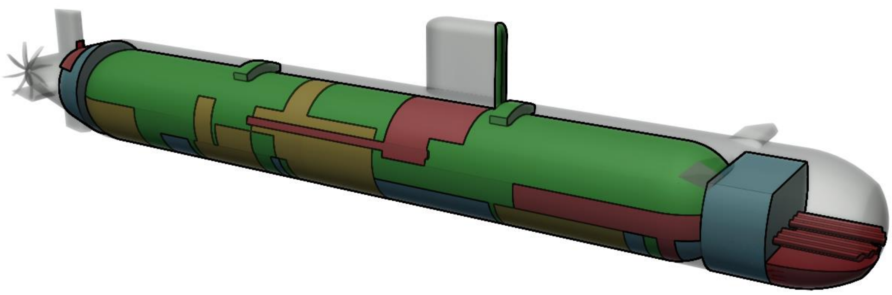

Figure H1 – Three-Dimensional View of SUPERB-Generated UCL 5,000 Tonne SSN

H.1.2 SECTION VIEW

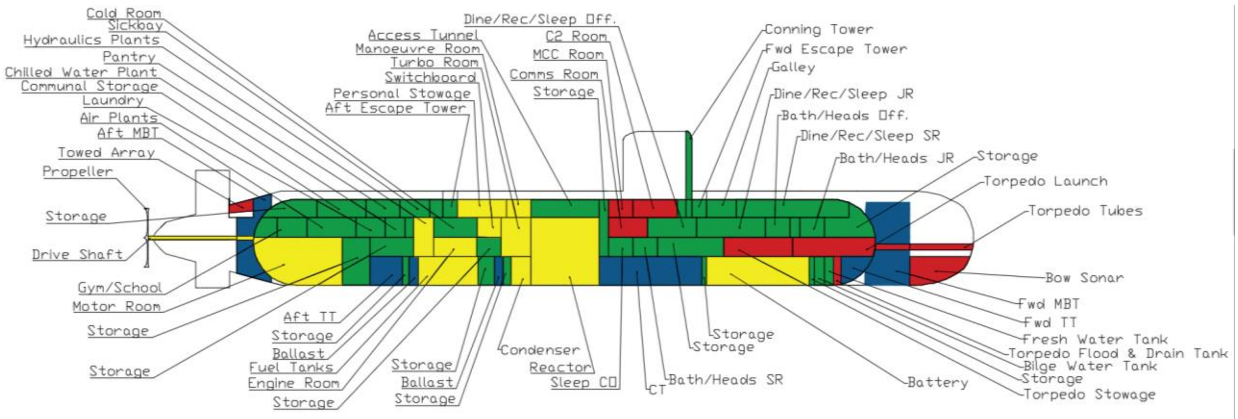

Figure H2 – Section View of SUPERB-Generated UCL 5,000 Tonne SSN

H.1.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H1 – Key Characteristics of SUPERB-Generated UCL 5,000 Tonne SSN

Characteristic	Value
Submerged Displacement [Tonnes]	5,450
Reserve of Buoyancy [%]	11
Length [m]	95.6
Maximum Speed [knots]	32
Primary Power	Nuclear – 1 x 37 MW
Secondary Power	Diesel – 2 x 1.1 MW
Weapons	12 HWT and 6 ASM; 6 Torpedo Tubes
Crew	106
Patrol Days	82

H.2 ‘TRAFALGAR’ SSN

H.2.1 THREE-DIMENSIONAL VIEW

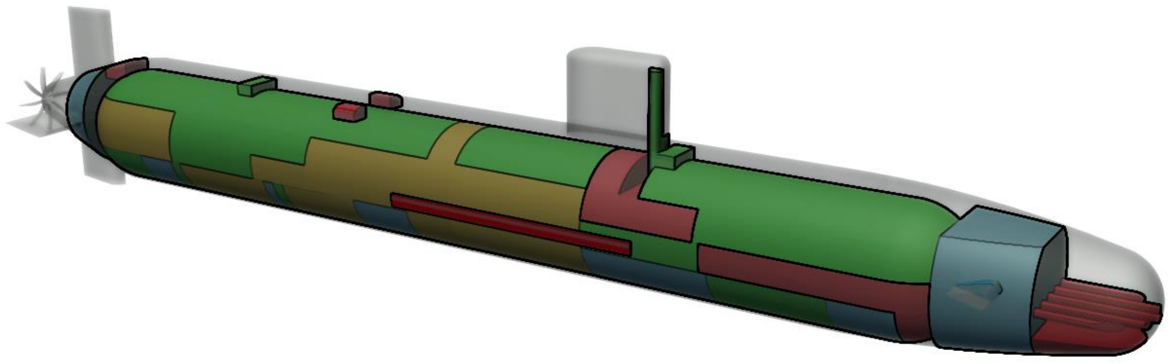

Figure H3 – Three-Dimensional View of SUPERB-Generated ‘Trafalgar Class’ Example Submarine

H.2.2 SECTION VIEW

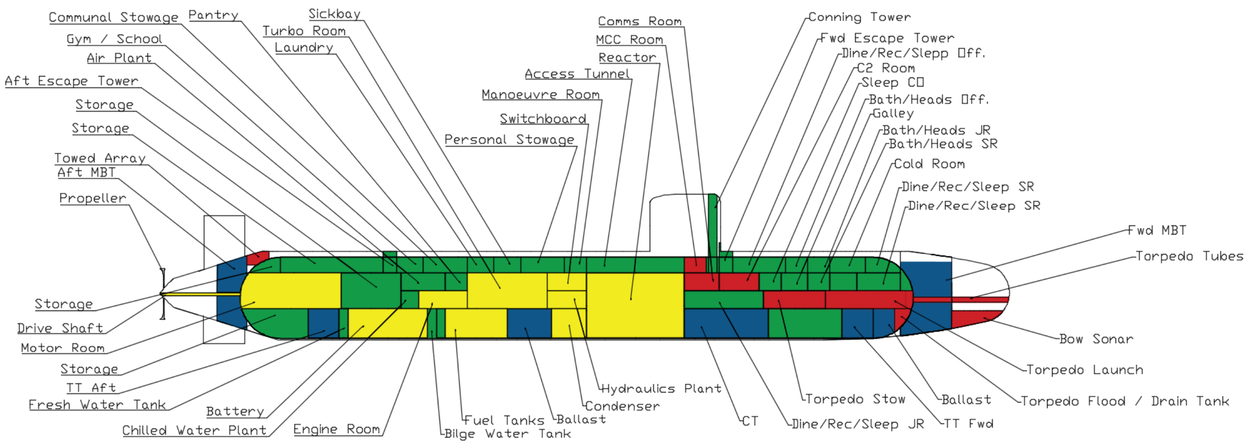

Figure H4 – Section View of SUPERB-Generated ‘Trafalgar Class’ Example Submarine

H.2.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H2 – Key Characteristics of SUPERB-Generated ‘Trafalgar Class’ Example Submarine

Characteristic	Value
Submerged Displacement [Tonnes]	5,300
Reserve of Buoyancy [%]	10.4
Length [m]	108.9
Maximum Speed [knots]	34.4
Primary Power	Nuclear – 1 x 33.5 MW
Secondary Power	Diesel – 2 x 1.1 MW
Weapons	20 HWT and 20 LAM ; 5 Torpedo Tubes
Crew	87
Patrol Days	83

H.3 'LE REDOUTABLE' SSBN

H.3.1 THREE-DIMENSIONAL VIEW

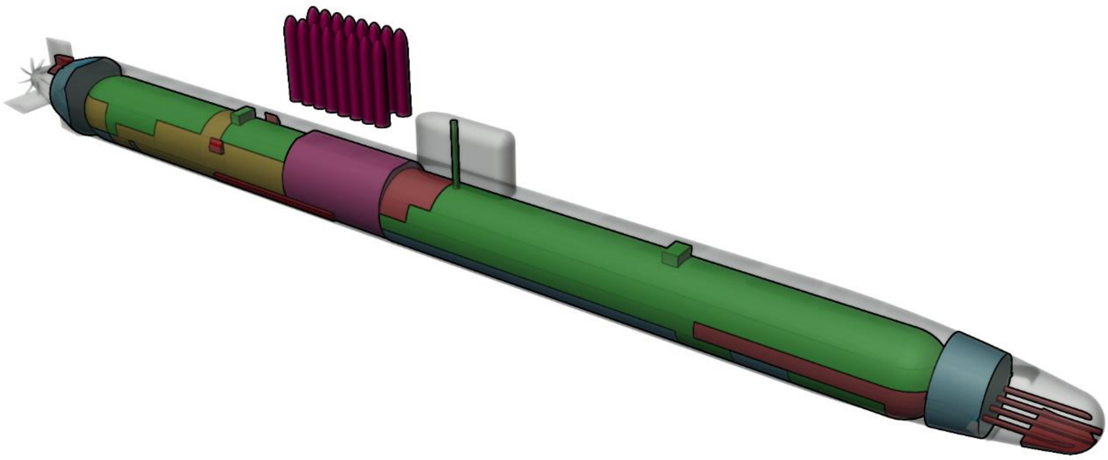

Figure H5 – Three-Dimensional View of SUPERB-Generated 'Le Redoutable Class' Example Submarine

H.3.2 SECTION VIEW

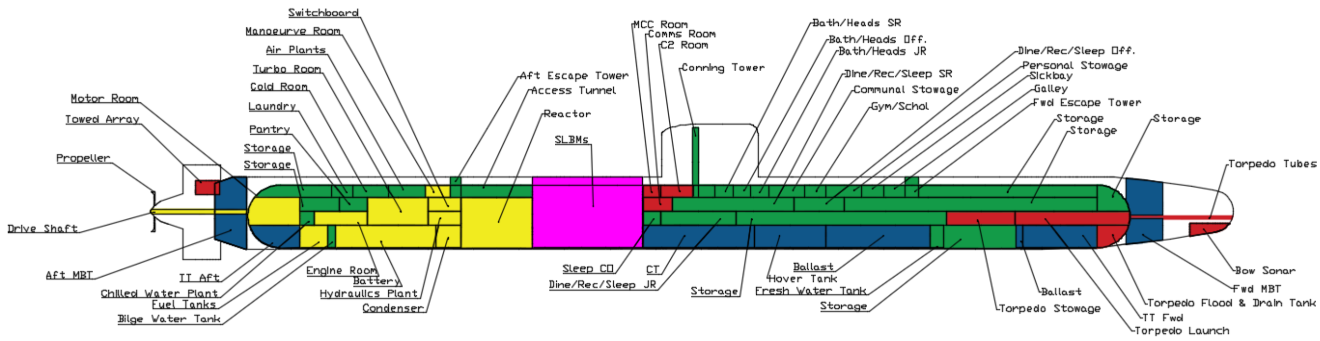

Figure H6 – Section View of SUPERB-Generated 'Redoutable Class' Example Submarine

H.3.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H3 – Key Characteristics of SUPERB-Generated 'Redoutable Class' Example Submarine

Characteristic	Value
Submerged Displacement [Tonnes]	8,940
Reserve of Buoyancy [%]	11.1
Length [m]	160
Maximum Speed [knots]	27
Primary Power	Nuclear – 1 x 15 MW
Secondary Power	Diesel – 2 x 1.1 MW
Weapons	8 HWT and 6 ASM; 4 Torpedo Tubes; 16 ICBM
Crew	115
Patrol Days	89

H.4 'A26' SSK

H.4.1 THREE-DIMENSIONAL VIEW

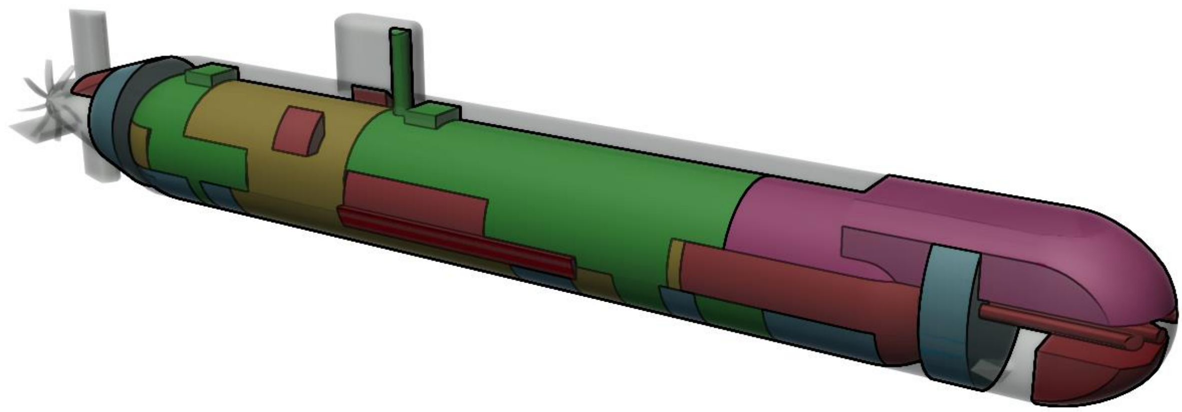

Figure H7 – Three-Dimensional View of SUPERB's Version of Saab's A26 SSK

H.4.2 SECTION VIEW

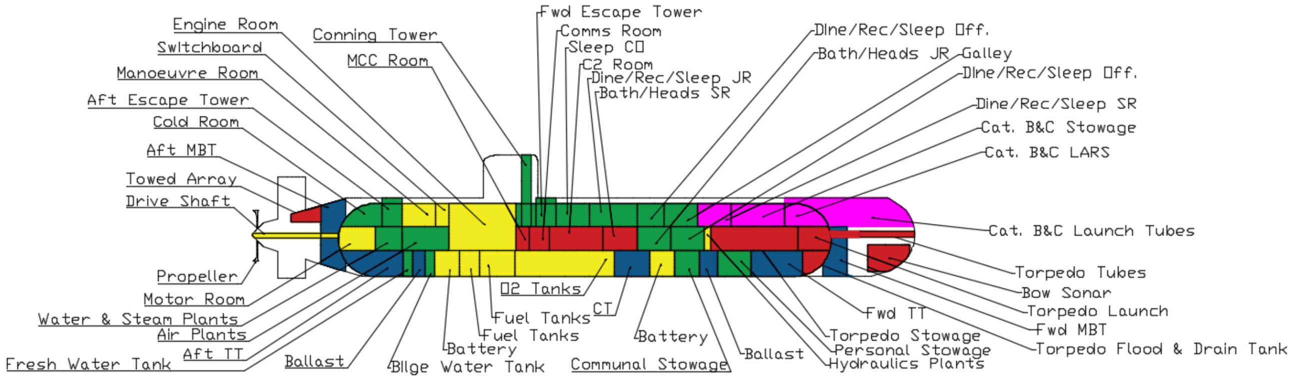

Figure H8 -Section View of SUPERB's Version of Saab's A26 SSK

H.4.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H4 – Key Characteristics of SUPERB's Version of Saab's A26 SSK

Characteristic	Value
Submerged Displacement [Tonnes]	2,000
Reserve of Buoyancy [%]	6.0
Length [m]	65.4
Maximum Speed [knots]	12.9
Primary Power	Stirling Engine – 1 x 0.98 MW
Secondary Power	Diesel – 3 x 1.4 MW
Weapons	2 ASM and 4 HWT; 4 Torpedo Tubes; 8 SLMMs
UUVs	4 x 850 kg
Crew	37
Patrol Days	45

H.5 BRADBEER’S SSKN CONCEPT – MORE CONSTRAINED VERSION

H.5.1 THREE-DIMENSIONAL VIEW

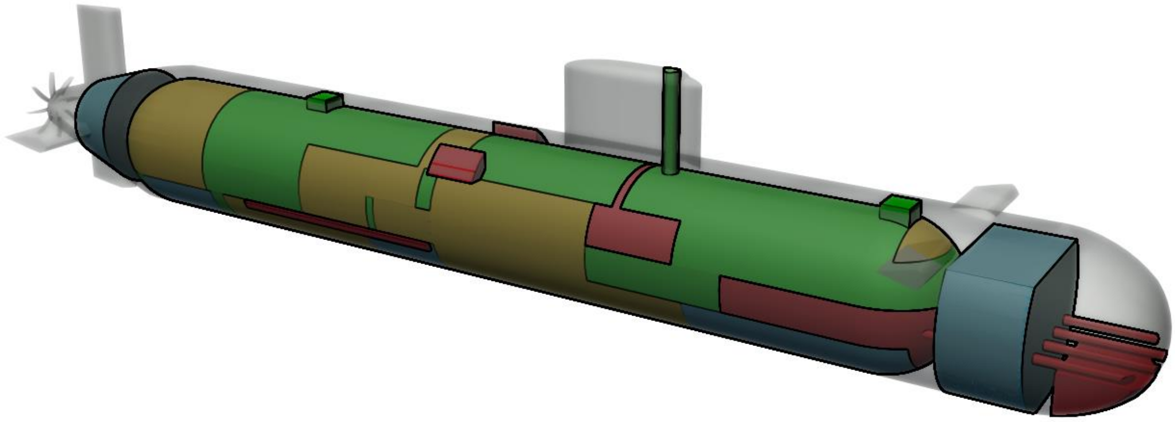

Figure H9 – Three-Dimensional View of SUPERB's Interpretation of BRADBEER’S SSKN Concept (with a More Constrained Arrangement)

H.5.2 SECTION VIEW

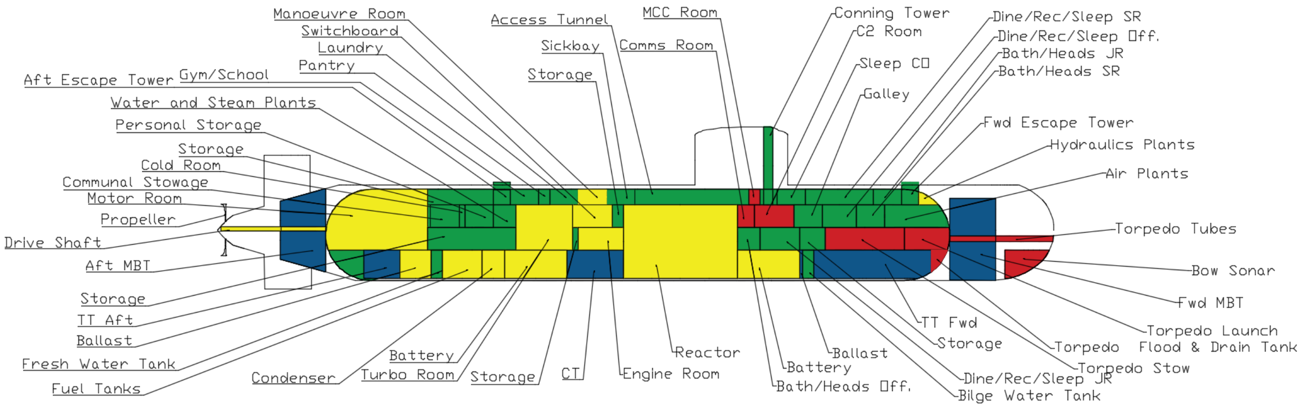

Figure H10 – Section View of SUPERB's Version of BRADBEER’S SSKN Concept (with a More Constrained Arrangement)

H.5.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H5 – Key Characteristics of SUPERB's Version of BRADBEER’S SSKN Concept (with a More Constrained Arrangement)

Characteristic	Value
Submerged Displacement [Tonnes]	4,950
Reserve of Buoyancy [%]	14
Length [m]	88.9
Maximum Speed [knots]	29
Primary Power	Nuclear –1 x 19.5 MW
Secondary Power	Diesel – 1 x 1.6 MW
Weapons	20 HWT and 6 ASM; 4 Torpedo Tubes
Crew	42
Patrol Days	45

H.6 BRADBEER'S SSKN CONCEPT – LESS CONSTRAINED VERSION

H.6.1 THREE-DIMENSIONAL VIEW

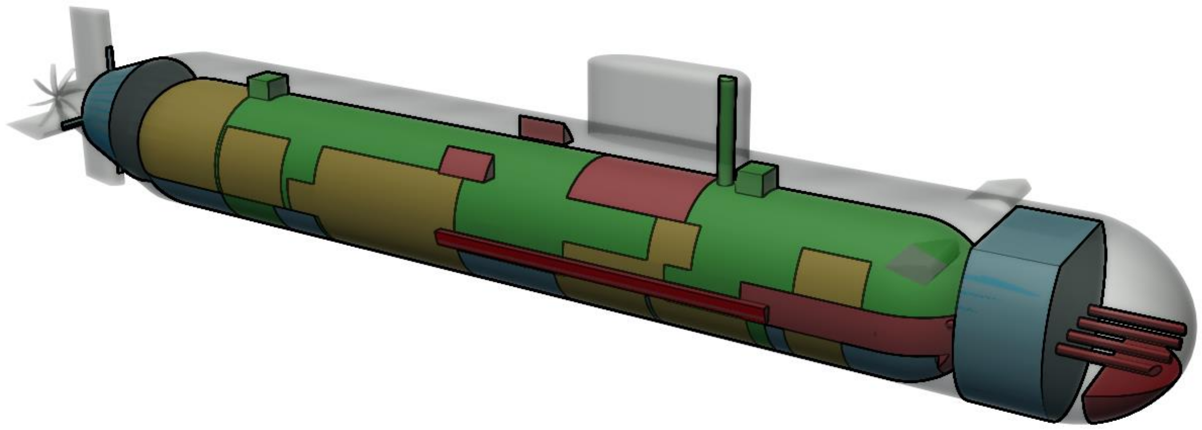

Figure H11 – Three-Dimensional View of SUPERB's Version of BRADBEER'S SSKN Concept (with a Less Constrained Arrangement)

H.6.2 SECTION VIEW

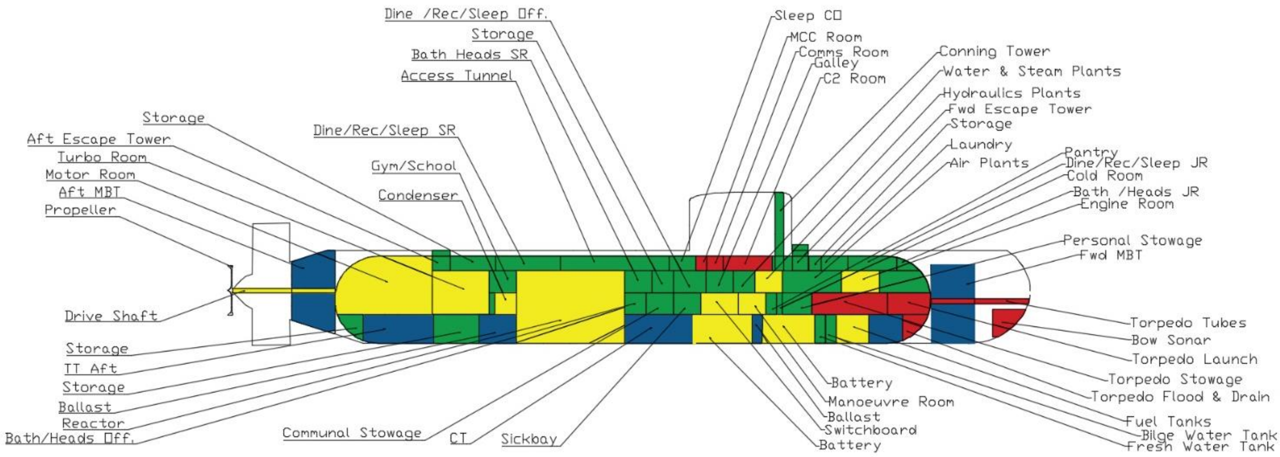

Figure H12 – Section View of SUPERB's Version of BRADBEER'S SSKN Concept (with a Less Constrained Arrangement)

H.6.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H6 – Key Characteristics SUPERB's Version of BRADBEER'S SSKN Concept (with a Less Constrained Arrangement)

Characteristic	Value
Submerged Displacement [Tonnes]	4,950
Reserve of Buoyancy [%]	14
Length [m]	88.9
Maximum Speed [knots]	29
Primary Power	Nuclear – 1 x 19.5 MW
Secondary Power	Diesel – 1 x 1.6 MW
Weapons	20 HWT and 6 ASM; 4 Torpedo Tubes
Crew	42
Patrol Days	45

H.7 BMT'S SSGT CONCEPT (SUPERB'S INTERPRETATION)

H.7.1 THREE-DIMENSIONAL VIEW

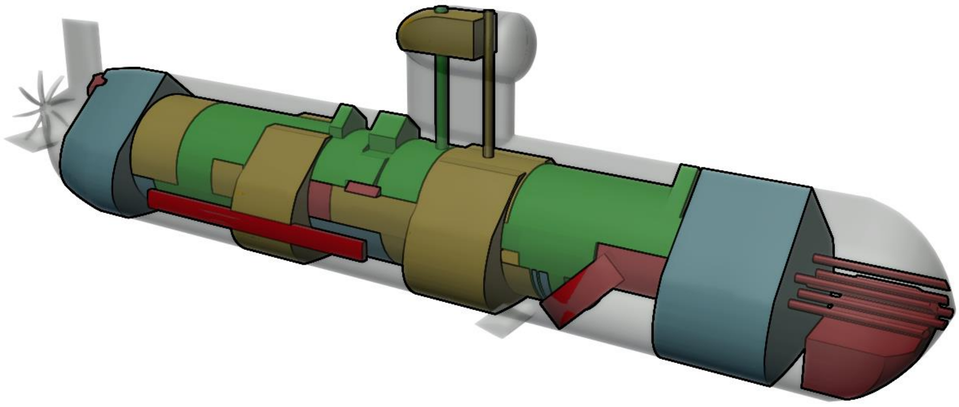

Figure H13 – Three-Dimensional View of SUPERB's Version of BMT's SSGT Concept

H.7.2 SECTION VIEW

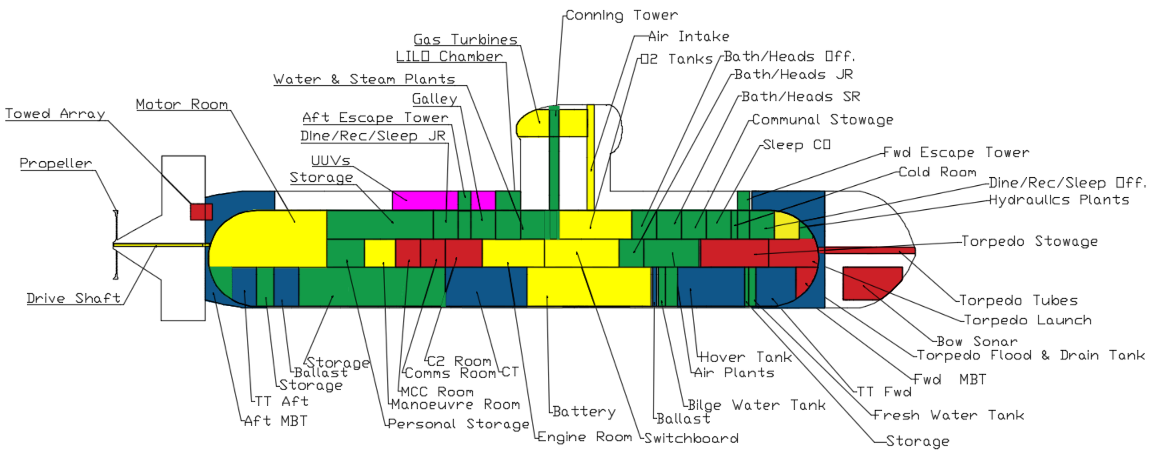

Figure H14 – Section View of SUPERB's Version of BMT's SSGT Concept

H.7.3 KEY CHARACTERISTICS OF SUPERB-GENERATED VERSION

Table H7 – Key Characteristics of SUPERB's Version of BMT's SSGT Concept

Characteristic	Value
Submerged Displacement [Tonnes]	4,195
Reserve of Buoyancy [%]	13.4
Length [m]	88.3
Maximum Speed [knots]	30.9
Primary Power	Gas Turbine – 2 x 5.2 MW
Secondary Power	Fuel Cell (APEM) – 3.85 MW
Weapons	8 HWT; 4 Torpedo Tubes; TLAM (VLS)
UUVs	4 x 10,000 kg
Crew	35
Patrol Days	60

APPENDIX I - FULL DESCRIPTION OF THE RESEARCH'S TACTICAL ISSUES

I.1 INTRODUCTION

The research at a tactical level is now discussed. This discussion of the issues mirrors the sequence in which different topics have been discussed in full. This would be the State of the Art review and the three novel components (USGOT, SUPERB and the NPF approach).

I.2 ISSUES RASIED BY THE STATE OF THE ART REVIEW

I.2.1 NEED FOR A 'GENERIC' SUBMARINE DESIGN TOOL

The review of the State of the Art indicated that a wide variety of concepts, especially concerning payload configurations, are considered during the concept exploration stage of a submarine design incorporating novel technology. SUPERB has been designed to meet the research proposal that emerged from the State of the Art review, namely the need to generate a wide variety of SSH(N) potential submarine concept designs in the unrefined solution space. This tool has been labelled a "generic" tool, as it is considered it should be able to generate novel submarine concept designs within the limits of practicality and the available information, That is to say, SUPERB needs to produce results in a sensible timeframe (around an hour). It is not claimed that SUPERB could produce *any* feasible submarine design, given it is limited by the extent of its algorithms and the data supplied to it by the concept designer.

From the State of the Art review, it was concluded that the generation of a large number of widely different concept designs needs to be produced using computer-based tools, so that they can be generated within a practical period (considered to be of the order of around three weeks). It was proposed that the tool that became SUPERB should produce designs (including arrangements) in a highly automated manner. SUPERB, however, is still directed by the designer, as the designer provides *a priori* knowledge and data to the Mathematical Modelling Module of SUPERB and specifies the values for top-level input variables from which necessary data on equipment and physical features can be inserted into SUPERB. This implies design decisions are split between those made by the designer and those hard-wired into SUPERB.

SUPERB has been designed to be readily interrogated (i.e. it is not a ‘black box’) since the computer code has been entirely and accessibly written in MATLAB, and is intended to ensure that the flow of data during the execution of SUPERB can be easily monitored. However, this currently needs to be tested for confirmation. This intent will ensure that the designs generated by the tool could be examined to verify the processes adopted by using the tool. Van der Nat has provided a definition of a ‘flexible’ design tool for SUBCEM (van der Nat, 1999). He states that new knowledge could be easily integrated and thus, as proposed in the State of the Art review, for any ‘generic’ design tool produced to generate concept designs, such as SSH(N)s, new knowledge needs to be easily integrated. By programming SUPERB in MATLAB, it should have the flexibility to incorporate new knowledge, since the code is easily accessible. Furthermore, knowledge can be readily implemented due to the generic nature of encoding the properties of the design’s compartments. This should make incorporating new properties into the arrangement method (Compartment X-Listing) virtually seamless. An example of this would be the incorporation of a gas turbine into the modified version of SUPERB to reproduce BMT’s SSGT concept (see Section 5.4). Another example of flexibility in SUPERB is the incorporation of knowledge obtained for the design characteristics of some novel UUV payloads that could be carried by an SSH(N, which has been captured to a limited extent using the bespoke OA tool, USGOT.

I.2.2 ARRANGEMENT APPROACH

A procedure for generic submarine design based on Burcher and Rydill’s (1994) procedure was adopted as the only one considered viable (and available) for the concept design of novel submarines, such as the SSH(N). The procedure, however, does not cover how to arrange compartments and equipment it, merely generates them. Thus, producing an arrangement approach was considered in its own right, as well as being an integral part of SUPERB. The State of the Art review did not reveal any existing approaches that seemed readily capable of fulfilling the requirements of an automatic and ‘generic’ approach to arrangement. The new approach, the Compartment X-Listing Approach, requires input similar to that described by van der Nat (1999) to generate some characteristics for DBBs from a set of top-level characteristics, via the Mathematical Modelling Module of SUPERB.

A computer-based packing algorithm, similar to the one outlined by van Oers et al. (2009), was suggested in the State of the Art review as a method to produce a wide range of concept designs. Van der Nat (1999) indicated that the order of allocating compartments within an arrangement could be important in incorporating packing algorithms. Thus, it was concluded that the Compartment X-Listing approach should control the order in which compartments are arranged, under the influence of the Constraint Profile from the first and second Arrangement Steps. The third Arrangement Step of Compartment X-Listing is the packing stage. The generation of benchmark designs with arrangements suggests that the packing sequence used by Compartment X-Listing is appropriate for use within SUPERB when generating novel concept designs, such as SSH(N)s.

The packing of compartments is governed by four hierarchical rules, which are intended achieve a ‘good’ and balanced arrangement and be adaptive or ‘dynamic’ (i.e. responsive) to the arrangements of compartments, based on those compartments already located. This is an extension of the localised optimisation of packing efficiency used in Van der Nat’s (1999) SUBCEM tool and in Zandstra’s (2014) investigation into dynamically adapting packing rules, which are dependent on the systems the designer has selected to comprise a design for ships.

The DBB approach, first proposed by Andrews (1981), is used as a basis for SUPERB to structure the description of compartment properties (see Appendix D Section D.9) which the Compartment X-Listing approach uses to generate an arrangement. Pawling & Andrews (2011) have used Paramarine to demonstrate that a DBB approach could produce feasible (and unorthodox) SSHN designs. It was therefore concluded that a bespoke arrangement approach, based on using DBBs, ought to be devised to perform heavily automatic arrangements (unlike Paramarine’s ‘manual’ allocation of DBBs). It was considered that an ‘automatic’ arrangement would still require some limited (but not direct) human direction upstream in the design process, such as for defining tankage objects. The human direction was also considered necessary for style decisions in producing a specific design since SUPERB itself cannot make style decisions. This is unlike the DBB approach applied by the UCL research team for locating ‘manually’ compartments, since this is driven entirely by the designer using Paramarine.

It was considered inappropriate to use a genetic algorithm based approach for producing submarine arrangements in SUPERB, as this would require devising and optimising a whole-boat level objective function[1]. It was considered such a function would not be suitable, due to the difficulty in defining it accurately at the low level of detail in concept design, coupled with the issue of multiple functions governing the design of naval vessels. This was considered especially important for novel concepts, which are not 'type' ship evolution-based designs, since any novel concept vessel, such as the SSH(N), is not going to have a well-defined concept of operations. The USGOT OA was intended to be indicative, rather than definitive of the overall UUV fleet's performance. Thus, genetic algorithms, using whole-boat level objective functions were concluded to be inappropriate. Furthermore, the approach was not deemed practical for producing arrangements for the broad range of potential designs that should be considered, when extensively exploring the unrefined solution space for the new concept of an SSH(N).

The University of Michigan's ISA approach (Parsons, et al., 2008) fits spaces inside a predetermined hull form and subdivision that have been generated from a previous design process, which has been concluded as unsuitable for exploring novel concepts, such as SSH(N)s. However, TU Delft's Packing Approach (van Oers, 2011) uses a genetic algorithm to produce layouts that rely on some MOE at the local arrangement level, using a database of relative locations. In terms of information required to generate an arrangement (the database used in the Packing Approach), this is similar to the candidate's Compartment X-Listing approach. The second Arrangement Step in the Compartment X-Listing approach dealing with Functional Constraints (see Figure 17 on page 94) operates at the local level and applies constraints to individual compartments to meet a designer imposed database of arrangement needs. The use of Style Preferences is considered unique to Compartment X-Listing and intended to promote arrangements that a designer would consider favourable at the whole-boat level. It is intended that using Style Preferences to obtain a set of designs with preferred arrangements should be faster (due to reducing the number of possible arrangements) than using an 'unguided' generic algorithm, which (typically) goes through a series of generations to produce a feasible set of arrangements, assuming feasibility is specifiable.

[1] The definition of whole-boat objective functions is considered to include meeting a set of specific predefined whole-boat objectives, such as by Duchateau, et al (2015).

Chapter 5 presented a series of submarine arrangements using the Compartment X-Listing approach, which are considered to be 'good', i.e. naval architecturally balanced designs to a concept level with arrangements with preferred style characteristics, as per the metrics devised for the Style Preferences allocated for the first Arrangement Step. It is considered that this suggests that the Compartment X-Listing approach does not need further 'optimisation' using a genetic algorithm, assuming an optimisation criterion was executable. The arrangement process using SUPERB took in the order of tens of minutes, indicating that it should be sufficient for the multiple executions of SUPERB necessary to conduct a broad exploration of the solution space for novel submarine concepts. The research presented to date does not compare the speeds of arrangement production using Compartment X-Listing against adopting a genetic algorithm based approach to generate a set of conceivable and balanced arrangements. Thus, currently, it can only be concluded that Compartment X-Listing is a plausible submarine arrangement approach, which may be faster and more designer responsive than any current alternative.

I.2.3 THE NATURE OF APPROACHES TO 'CONVENTIONAL' CONCEPT EXPLORATION FOR SUBMARINESS

In the State of the Art review (Section 2.3) it was considered important to explore how 'conventional' concept exploration could be performed, following the production of the refined solution space, as the design points from the production of the refined solution space are the basis for undertaking the rest of concept exploration. Thus, the selection of an approach for 'conventional' concept exploration might also be applicable to wider concept exploration needs. It was concluded that, for differing reasons, both the Set-Based Design (SBD) approach put forward by Singer et al. (2009) and discrete architecturally led DBB approach proposed by Andrews (2003b) have limitations in undertaking concept exploration of the refined solution space for novel vessels, such as the SSH(N). Especially for SBD, an *a priori* defining of the bounds of the refined solution space seemed necessary for use in the concept exploration of the refined solution space for novel designs.

The SUBCEM tool, created by van der Nat (1999) suggested that a 'generic' submarine design tool using a semi-automatic architectural approach, as with SUPERB, could be used to populate the refined solution space on which to base 'conventional' concept exploration. It was concluded from Chapter 2 that ‘conventional’ concept exploration using an approach with discrete designs possessing arrangement is advantageous over SBD if the designer has not been constrained beforehand on the definition of the refined solution space. The uncertainty in incorporating novel technologies into designs, and hence defining the sets of systems SBD would use to generate submarine ‘designs’, implies difficulty in adequately defining the refined solution space, if SBD was applied to concept exploration. Furthermore, it is considered that without a DBB level of concept definition, it is unlikely that the designer can obtain a worthwhile understanding of the impact of new technology on whole ship (or submarine) design in the Concept Phase of design.

The NPF approach’s second stage, during which the Balanced Pareto Front is determined, has been seen in the test exploration of the SSH(N) concept (in Section 7.2), to produce a focused set of non-Pareto dominated and concept level balanced designs to which a discrete architecturally led approach could be applied to inform concept exploration. This implies that concept exploration using a discrete architecturally led approach is possible and that an architectural approach is needed as part of SUPERB. The successful incorporation of knowledge obtained from the USGOT simulations in the test exploration also suggests that such an approach could address concept exploration, including unorthodox submarine designs, but would lack the confirmation of the position of the BPF without the large number of solutions produced using SUPERB, or a similar semi-automatic design tool.

I.3 ISSUES RASIED BY USGOT

The few missions simulated by USGOT (see Chapter 3) were seen to provide knowledge on the size and composition of UUV payloads for missions perceived to be very resource intensive. In particular, the indication that such UUV payloads would have a large total displacement (typically in excess of 50 tonnes), would be a radically different from the current UUV payloads being considered for submarines. For example, only a few smaller UUVs are specified in Saab’s A26 submarine (Saab, 2015).

The USGOT tool was limited to considering a few example UUV missions, considered to be heavily resource taxing and demanding highly capable UUVs. It is conceivable that during an actual investigation into the SSH(N) concept, a less restricted range of UUV missions might be adopted. This in turn, could mean that different measures of effectiveness (MOEs) might to have to be devised. The MOE used by USGOT in the studies to date was mission-specific and thus it followed that different missions meant different MOEs. A possible addition to the list of simulation missions could be mine countermeasures (MCM) and the MOE devised for MCM would likely be driven by the rate of area coverage of UUVs, as this would reflect the rate at which mines/unexploded ordinance could be located and neutralised. This could be important for certain operations, such as the preparation for an amphibious landing or maintaining clear strategic shipping routes. Pre-calculating the effectiveness of a limited number of UUV payloads (i.e. before using SUPERB to generate a SSH(N) design), was seen to preclude undertaking very large and computationally demanding batch runs in SUPERB of every possible combination of numbers of different UUV for every design generated.

The USGOT simulations presented provided insight into the relative importance (according to the MOE used) of the different categories of UUVs that make up a UUV payload. It was seen that the Category A UUV/MUVs was predominant in driving the effectiveness of a UUV fleet to perform missions that were perceived as resource taxing. Furthermore the Category A UUVs' influence on the overall weight of a UUV payload was of particular importance for SSH(N) designs. The importance of Category A UUVs points to where a large portion of the design effort should be focussed in order to incorporate these UUVs and their supporting equipment, such as LARS, into the overall SSH(N) design.

USGOT's usefulness could be explored through a sensitivity study on the size (or any other design characteristic) of the UUV fleet carried by an SSH(N) in order to perform specific UUV missions. The simulations described in Chapter 3 used three UUV categories and attributed to them characteristics which were considered to be conceivable but not necessarily currently deliverable. It is considered that particular attention in any sensitivity study should be paid to the design of the Category A UUV. To date, very few UUVs above around 3,000 kg displacement have become available (see Appendix B Section B.1). It is anticipated that as unmanned underwater operations become more commonplace, further developments of large UUV/MUVs will occur to facilitate more complex multi UUV operations, such as those simulated by USGOT. Investigative work into identifying a Category A UUV/MUV that could be more confidently be described as realistic would improve the usefulness of further SSH(N) studies using SUPERB. A sensitivity study on UUV performance and SSH(N) would also improve the confidence in the accuracy of the assumed overall payload size and composition assumed so far.

Furthermore, the analysis of UUV nets could also consider threat vectors which did not target the SSH(N). It is considered that this would be a more realistic representation of operations.

I.4 ISSUES RASIED BY SUPERB

I.4.1 MATHEMATICAL MODELLING USED

The utility of the Mathematical Modelling Module in SUPERB has been limited by the range of equipment and physical features that has been programmed into it to date. Currently, SUPERB is limited to considering pressure hulls with one midsection diameter. Historically, there have been some attempts at multiple pressure hull configurations, for example, twin pressure hulls (e.g. Russian *Typhoon*-class (Naval-Technology.com, 2014b)), most single hulls have cones and transitions (Faulkner, 1983) and triple pressure hulls arranged in a triangular formation Dutch *Dolfijn*-class (Heiszwolf, 2000). SUPERB could be extended to model different pressure hull configurations and ranges of unorthodox designs in order to explore a wider region of unrefined solution space.

The Mathematical Modelling Module of SUPERB was successfully altered to approximately recreate the triangular casing used on the BMT SSGT (BMT Defence Services, 2015), demonstrating the ability ('flexibility') of SUPERB to be programmed to consider unusual physical features. Further exploration could investigate other submarine concepts to determine whether the SUPERB tool could be appropriately modified. It is considered that this could be important if SUPERB is to be used as a research tool, as it might show the extent to which SUPERB could explore concepts other than the SSH(N).

Currently, the Mathematical Modelling Module is limited by the data and knowledge from which the mathematical models are constructed. Thus, SUPERB cannot access unrefined solution space regions for which data is lacking. Hence, prior to using SUPERB for an exploration of a novel concept, an investigation of relevant and accessible data would be required. Such an investigation ought to include explorations of existing technologies as well as novel ones, to test data reliability. Clearly, some external limitations might limit this exploration of the unrefined solution space. For example, a politically driven decision to exclude the consideration of nuclear reactors for submarine propulsion[1], regardless as to whether in might be technologically advantageous in meeting operational requirements.

I.4.2 ARRANGEMENT APPROACH

The Compartment X-Listing approach relies on a selection of Style Preferences and Functional Constraints and this selection is intended to ensure that a conceivable and naval architecturally balanced arrangement is produced. The sum of Functional Constraints and Style Preferences selected has been termed the "Constraint Profile". Thus the Constraint Profile will strongly influence the arrangement produced using Compartment X-Listing. The 'logistical effort' measure that reflects the ease of movement of personnel and equipment within the submarine design is a significant influence on the generated arrangement. In Subsection 5.3.3 100 SSTs (teleportable SSKs) that have been generated by SUPERB, each one having a different profile of compartment locations relationships for the mathematical 'optimisation' of the 'logistical effort' Style Preference, described in Subsection 4.5.2. The significant differences seen in the 100 generated SST arrangements by Compartment X-Listing (see Figure 28 on page 126) indicated that the choice of compartment locations relationships made by the designer is important. Thus, further investigations could be undertaken to determine the extent of relationship choices to see how the 'logistical effort' affects arrangements. Of particular interest could be the sensitivity of the individual relationships between compartment types, as a means of revealing design drivers. In such an experiment, each compartment locations relationships could take any value between -1 and 1. This choice is considered to demonstrate that the relative attraction between pairs of compartments could be handled during the mathematical 'optimising' of the 'logistical effort'.

Thus, for instance, it may transpire from undertaking a sensitivity study of individual relationships between compartment types that the level of attraction/repulsion between the accommodation compartments and the C2 compartments might be very significant. The visibility provided by programming Compartment X-Listing in MATLAB can ensure that the process to calculate the

[1] As an example, the Australian government has stated that it has precluded the use of nuclear-powered propulsion for its next generation of attack submarines to replace the current *Collins*-class (Commonwealth of Australia, 2012).

‘logistical effort’ is accessible and thus, could analysed. This, in turn, could reveal the reasons for the significance of a particular relationship and gain insight for a given design.

The ‘logistical effort’ calculated using the equations in Subsection 4.5.2 provided distances from compartment centroid to compartment centroid in both the longitudinal and vertical directions. This was done to simplify the calculations, easing the mathematical ‘optimisation’ by solving them explicitly, and hence, quickly. More realistically, the movement of personnel and equipment between compartments within a submarine is along a series of paths. These paths can be along decks and up/down ladders and hence movement could be modelled instead as less realistic vertical and longitudinal distances. Furthermore, some possible routes are likely to be infeasible – for example, one should not be able traverse straight through a nuclear reactor, but instead have to use the access tunnel. A model of the ‘true’ distances between compartments for the ‘logistical effort’ could therefore be constructed. However, it would almost certainly mean the ‘logistical effort’ could not be mathematically optimised explicitly and instead require a potentially computationally expensive algorithm to search for the preferred layout solution. Investigations showed that currently the execution of the all the sub-steps involved in the first Arrangement Step of Compartment X-Listing took a modern CPU[1] approximately 200 seconds. It is considered that adding complication to the ‘optimisation’ of the disposition of compartments driven by the logistical effort might increase the calculation time to what may well be considered unsatisfactorily (e.g. about ten minutes).

A further aspect of the current arrangement approach is that the modelling of some layouts will not be solely dependent on deck heights and vertical distributions, since these are not homogenous throughout the potential submarine. If heterogeneous decks have to be modelled by SUPERB, then generating a layout is likely to become more complicated. Other sub-steps (i.e. Style Preferences) of the first Arrangement Step include a notional positioning of compartments to provide longitudinal balance and acceptable submerged stability characteristics (see Figure 18 on page 96) by ensuring the centre of gravity and of submerged buoyancy are positioned essentially longitudinally coincident and significantly vertically separated (>4% of PH diameter, see Burcher & Rydill (1994)). As the ‘logistical

[1] Built circa 2012

effort' affects the capability of achieving a feasible layout, so the added complexity of heterogeneously distributed decks is considered likely to require a more complex algorithm to produce acceptable arrangement of compartments with longitudinal balance and acceptable submerged stability. This complexity would mean the longitudinal and vertical placement of compartments are interdependent, due to heterogeneous distribution of decks, since the longitudinal position of a compartment affects the vertical position(s) of the deck(s) on which the compartment can be placed.

The influence of Functional Constraints in the Constraint Profile has been explored in Subsection 5.2.2 by comparing Bradbeer's SSKN (Bradbeer, 2015) against two SUPERB-interpreted[1] arrangements. The first had a Constraint Profile selected to promote an orthodox arrangement style and the second a Constraint Profile omitting many of orthodox style-promoting Functional Constraints, enabling a potentially unorthodox arrangement style. The overall agreement between the original SSKN produced by Bradbeer and the arrangement for the same project using SUPERB while adopting a relaxed Constraint Profile (by reducing the Functional Constraints), indicated that a relaxed Constraint Profile potentially facilitates the generation of unorthodox arrangements. It was considered that the Bradbeer SSKN concept is an unorthodox design and so agreement with the SUPERB-generated arrangement (adopting the relaxed Constraint Profile) would demonstrate unorthodox designs could be produced.

Section 5.2 indicated the selection of constraints affects the arrangements produced by Compartment X-Listing, while Duchateau et al. (2015) observed for surface vessels that successive generations of arrangement can be guided by the selection of a set of constraints. However, the current research has been limited to variations of Constraint Profile in Compartment X-Listing. This suggests a need to investigate further the effects of such selection to give an improved understanding of the influence of the Constraint Profile.

Furthermore, the good agreement in replicating Bradbeer's SSKN concept suggests that SUPERB can to some degree reproduce the actions of the designer in producing a submarine internal arrangement. This is considered fundamental if a large number of novel concept designs, likely to be required for a SSH(N) investigation, are to be generated by SUPERB in populating the unrefined solution space. Thus,

[1] See Subsection 5.1.1 for the definition of "interpreted".

arrangements being produced are conceivable and, ultimately, the designs emerging on the Balanced Pareto Front have preferred arrangements while achieving naval architectural balance.

The packing stage of the Compartment X-Listing (the third Arrangement Step – see Figure 17 on page 94) has so far only been achieved for pressure hull(s) with a consistent cylinder diameter – i.e. pressure hulls without waists and transitions. Furthermore, the end torispheres of a pressure hull have been represented mathematically as flat ends with the pressure hull end location averaged out to model torispherical PH ends. These two simplifications were made to simplify the creation of the X-List in the preceding two Arrangement Steps and were considered appropriate for broad level of detail definition at the concept level of design, but not suitable for subsequent stage in the design process. However, it is recognised that further studies ought to be undertaken to determine whether these simplifications are appropriate if SUPERB is to be used to investigate submarine concepts. Furthermore, the simplified PH cylindrical section hinders SUPERB's ability to investigate submarine concepts with unusual equipment and physical feature configurations and in turn the variety of unorthodox designs that could be explored. It also could disguise potential problems with unorthodox issues. For instance, a PH with a waist could conceivably prevent an unorthodox arrangement meeting a (hard) Functional Constraint by obstructing compartments in a manner similar to that illustrated in Figure 19 on page 99 by poorly sequenced compartment packing, and hence lead to naval architectural unbalance.

The approach for packing used by SUPERB cannot be said to be truly generic, as it has not been verified against a reasonable number of pressure hull geometries that could be said to represent *all* likely geometries. One way to address this would be to model volumes that are unavailable, due to waisting a pressure hull, as additional 'void' compartments. These compartments would have fixed locations and dimensions but with zero weight, as part of the overall pressure hull volume (defined by the computer). The volume accessible to 'real' compartments would then reflect the actual pressure hull geometry. A similar issue can be seen in Figure 21 on page 108 in Subsection 5.1.1, whereby a void between the forward Main Ballast Tank (MBT) and the Pressure Hull (PH) is formed in a SUPERB-generated submarine. This is due to the modelling of compartments as blocks in SUPERB with straight lines. Thus, it cannot represent the more complex geometry of the forward MBT and wrapped around the dome bulkhead. To ensure that the forward MBT partially wraps around the PH, a portion of the oversized forward MBT compartment (as it is shown in Figure 21 on page 108) is assumed to be unavailable due to the PH. This void cannot be eliminated in the current version of SUPERB as it is defined in the Mathematical Modelling Module before the arrangement packing. However, it may be possible in SUPERB's External Arrangement Program (SEAP) to model the space removed by the PH from the forward (and aft) MBT, depending on the relative longitudinal locations of MBT and PH. This would allow the spaces to be more properly modelled.

I.4.3 ANALYSIS MODULE OF SUPERB

The problem arising from the limited analysis appropriate during the concept exploration stage of the design process has been explored by Andrews (2013). Andrews pointed out that numerical analysis at this stage should not be blindly treated as 'black box', but rather the limitations and risks should be appreciated by the designer because there are unknown constraints on the design.

Currently, SUPERB lacks the ability to assess the influence on a concept design caused by hydrodynamics, and, in particular, manoeuvrability related aspects. This introduces a degree of uncertainty into the analysis of a design, which could in turn, significantly affect requirement elucidation. For example, knowledge of the hydrodynamic effect of the longitudinal position of the bridge fin, and thus whether it affects achieving naval architectural balance, could be used to guide the arrangement process and ensure it is placed in a preferred position. Such analysis was considered impractical due to time constraints and the level of design fidelity likely at the concept stage to conduct an assessment by SUPERB for each concept designs manoeuvring characteristics. A possible solution, which would be a classic concept get around, could be to approximately describe the hydrodynamic performance of a concept design using a set of pre-calculated lookup tables, in conjunction with some (simplified) hydrodynamic equations appropriate for manoeuvrability. However, the limits of such an approach should be well understood, given SUPERB's limited ability to model unorthodox concept designs.

Survivability from flooding is another design aspect that is not considered using SUPERB's analysis module, as it requires substantial modelling (Burcher & Rydill, 1994). However, with the generation of an arrangement by Compartment X-Listing, it could be possible to perform an assessment of a boat's ability to survive damage by undertaking a similar analysis to that using Paramarine's assessment tools.

The inclusion of such an assessment would then affect how the Measure of Tradable Performance Metrics (MoTPC) calculates the overall survivability of the design.

Along with the MoTPC, SUPERB also assesses the UPC of a design in UCL pounds. If SUPERB is used ‘in anger’ for the exploration of a submarine concept, a specific cost model would be implemented, instead of the one used in this research. Such a model ought also to consider the Through Life Cost (TLC) of a boat by modelling likely expenditure in service as well as its build cost. A further detail could be the cost consideration of fleet size and even the fleet’s interaction with the rest of a defence force. For example, the reduced cost of equipment due to the economy of scale, or political realities demanding the use of nationally produced equipment.

I.5 ISSUES RASIED BY THE NOTIONAL PARETO FRONT APPROACH

I.5.1 RESTRICTION ON THE ACCESSIBLE UNREFINED SOLUTION SPACE

The effectiveness of the proposed NPF approach in exploring the unrefined solution space for a novel design is limited by the mathematical modelling of the systems (and subsystems) that make up a given design being investigated. This would restrict the extent of any unrefined solution space. As explored in Subsection 6.3.2, top-level input variables that could take values from a continuous range have been discretised for sensible sampling, to limit the computational demands. Furthermore, SSH(N)s more readily bound the solution space compared to ships, as the design of submarines and UUVs are heavily constrained by the physical environment in which the operate. For example, there is a restriction in the variation of viable UUV LARS solutions. This means that some systems and, by extension, some unrefined potential submarine solutions would not be considered using SUPERB when investigating a novel submarine idea, such as the SSH(N). As computer speeds increase, the amount of computation possible in a given time should increase. This, in turn, should allow a greater range of sampled values – increasing the extent of unrefined solution space that is accessible for exploration.

I.5.2 STATISTICAL SAMPLING OF THE UNREFINED SOLUTION SPACE

Slovin’s formula (Altares, et al., 2003) for determining the statistical confidence level of a sampled population has been used to identify the sample size for generating the pool of potential designs through ‘smart’ sampling. The level of statistical confidence (90%) was chosen to measure confidence in the identification of underlying trends for high performance. Thus, the subset of sampled designs said to have high performance should (statistically) reflect the subset of designs with high performance from the full range of potential design. The occurrence of an anomalous identification of a preferred design characteristic value was assumed to be in a one-tailed confidence interval, with randomness modelled using a normal distribution and selected using a Monte Carlo simulation to populate the unrefined solution space. The normal distribution was adopted as this is typically used in applications where a population is sampled to identify trends that are not readily apparent, such as for political polling. The application of the normal distribution in political science has been described by King[1] (1988). King has also suggested that other models of distribution for sampling a population might be suitable for adoption, and so it is considered that an investigation could be taken into account for identifying a preferred distribution model for 'smart' sampling. Such an investigation could also address whether the confidence level could minimise both computational demands and provide sufficient confidence that the pool of potential designs is being satisfactorily modelled by sampling.

I.5.3 'SMART' SAMPLING ELIMINATING PARETO-DOMINATED AND INFEASIBLE DESIGN OPTIONS

'Smart' sampling has been assumed in Subsection 6.3.3 as statistically adequate to cover and represent the region(s) of interest, it also allows the computationally expensive synthesis of unbalanced submarine designs. Some of these potential designs could be assessed as likely to be unbalanced when applying the NPF approach, prior to design synthesis. It is considered that such an assessment could be based on other synthesised unbalanced designs that possess similar characteristics. For example, if a design is synthesised and found to have insufficient internal volume for an acceptable arrangement, a similar design with a very similar set of pressure hull dimensions (e.g. ±1% tolerance) would likely to also be unbalanced. The numerical definition of similarity could be the same as the fidelity of sampled values for a top-level input variable. It is proposed that a subroutine in the control program (an 'analytical engine') could be programmed to recognise why a certain design failed to achieve naval architectural balance. This could be accomplished by using error codes in the Analysis Module of SUPERB (outlined in Table D5 in Appendix D Section D.7.5), and could be expected to demand significantly less

[1] King (1988) said "*for continuous variables in ordinary regression analysis, the normal distribution is often … justified as the sum of many unmeasured variables*"

computation than synthesising unbalanced designs. The subroutine could be made to suggest the synthesation of potential designs in specific regions of the unrefined solution can be assessed as more likely to lead to balanced designs than the current NPF approach. The proviso of incorporating this subroutine is that there should be sufficient confidence in unbalanced designs being 'truly' infeasible, and that the aforementioned tolerance was suitable for identifying similar potential designs to already synthesised but unbalanced designs.

The Monte Carlo simulation was seen to model adequately the unrefined solution space resulting from the proposed 'smart' sampling, which reduced the unrefined space by using System Group (SG-level) Pareto Front analysis to reject regions in the unrefined solution space that were considered to contain potential designs comprising of infeasible system group options. The shape in the NPF plot of Figure 35, which shows the pool of unrefined but conceivable options for the design of SSH(N)s and, in particular, the NPF particularly showed a portion of the unrefined solution space, with potential designs which have been eliminated from consideration. This portion was the space above the NPF – i.e. potential solutions which would be high performing and cheap (as estimated using SUPERB's metrics). These designs were rejected due to violating SG constraints in the Mathematical Modelling Module of SUPERB (see Subsection 6.4.2), which are responsible for creating the SG-level Pareto Fronts that constitute naval architecturally balanced designs following synthesis.

Similarly, the 'bunching' of the unrefined potential solution options in Figure 35 towards the NPF could be taken as evidence that the 'smart' sampling feature performs as intended (see Subsection 6.4.2). Designs have been eliminated by 'smart' sampling in the unrefined solution space that could have possibly achieved naval architectural balance following synthesis, however, in Figure 38 they would then be seen to be Pareto-dominated by other potentially balanceable design options. However, the high density of design options (evidenced by the near coincidence of the NPF and Balance Pareto Front) suggests that a proportion of the pool of unrefined potential solution options in Figure 35 are not close to the Balanced Pareto Front, indicating that their generation is 'wasted'. The pool of unrefined potential options could be further reduced by a subroutine removing design options it determines to be Pareto-dominated. Furthermore, this subroutine could be written to update the pool of unrefined potential solution options dynamically as it 'learns' which of the characteristics of these designs is likely to lead to a reduced pool of solutions rather than those in Figure 38. This might be seen to be a more efficient use of computational resources through sampling a smaller region of unrefined solution space with an increased proportion of balanced submarines. This is because computational resources would not be as ‘wasted’ by synthesising as many unbalanced submarines.

I.5.4 REASONS FOR CONFIDENCE IN THE ADOPTED MEASURES OF ‘PERFORMANCE’ AND COST

Some 30 top-level input variables have been used in SUPERB to produce submarine designs from which cost and ‘performance’ are outputs (although some performance elements are also inputs, such as top speed). This approach was adopted instead of generating and searching a set of designs for one that has specific cost and whole-boat ‘performance’ points. This choice was made since multiple sets of system groups might be conceivably combined to achieve a specific set of features. Another reason for not using a specific cost and a set of whole-boat ‘performance’ features as input is that in doing so implies the designer knows *a priori* where the solution designs may approximately be found. This would be contrary to the raison d'être of the NPF approach which is that the approximate location of balanced designs will be unknown before SUPERB has been run (including Compartment X-Listing).

To remove doubt that both the cost and the MoTPC are essentially outputs from the choice of the size of the vessels generated by SUPERB, Figure 33 presents the submerged displacement for a range of potential designs with differing MoTPC and cost values. Submerged displacement was chosen as the investigated characteristic in the study presented in Subsection 6.2.2 as it was considered that if any design characteristic would comprehensively complete influence on MoTPC and cost, it would be submerged displacement. Thus, if submerged displacement was seen not to exclusively drive cost and ‘performance’, it could be assumed this applied to other design characteristics as well.

There is an expected broad trend in Figure 33, namely that larger vessels have a higher assessed performance and a high cost. Vessels with a greater displacement can typically accommodate a greater amount of equipment (which is responsible for a portion of the overall performance) than smaller vessels. However, typically the inclusion of a larger amount of equipment also results in a higher cost. However, Figure 33 also shows that for equally sized submarines, the performance (MoTPC) calculated by SUPERB can vary greatly, i.e. MoTPC (overall) values of between 40% and 70%. Some designs shown in Figure 33 have the same size and performance but differ in assessed costs. This is because there are multiple ways to which a specific overall performance value could be arrived at using the MoTPC metrics but with different design characteristics. The corollary is that a SUPERB-generated submarine design's MoTPC metrics and cost are not solely a function of its size. The MoTPC was thus considered a suitable metric for use in investigating design trade-offs for concept submarines and thus, appropriate to populate the unrefined solution space with potential designs by SUPERB. However, it is recognised that the MoTPC is based only on one set of weightings, which may be subject to bias. A sensitivity study could be undertaken to establish the effect of bias on the overall conclusions if the NPF approach was used for an actual investigation. It is proposed that similar studies, such as for the one presented in Subsection 6.2.2 for submerged displacement, be undertaken for other major design characteristics, such as maximum speed. Such studies could be enhanced if more than 10,000 potential designs were generated, as this would increase confidence that the results obtained were not anomalous. As stated in Subsection 6.2.2, the generation of submarines do not need to be synthesised and balanced designs validated, in order to investigate the mathematical models which describe submarine 'performance' and cost.

Significant differences between early concept design estimates and more refined definitions still in concept design[1], mean a design selected from the Balanced Pareto Front may not actually be the most attractive to the designer using some criterion, such as for value for money. By just considering one design, all future work on developing subsequent SSH(N) designs might be driven by the peculiarities of that design. Some of these peculiarities may point to a design solution that might be near the 'edge of the cliff' in terms of the cost versus performance. Furthermore, when avoiding the 'edge of cliff' consideration ought to also be paid to scope for altered requirements, which could force a previously 'safe' design solution to the cliff edge. Error in the cost, due to uncertainty at the concept level of definition, could make a selected design eventually appear unattractive. An analysis of a range of submarine designs could 'smooth out' this effect (providing synthesis is believable), which would

[1] For example, Andrews and Pawling (2008) presented a Littoral Combat Ship at four different stages of design in the Concept Phase of the design process. The ship's displacement rose from 2,830 te to 3,212 te, a difference of approximately 13.5%.

increase confidence in the design trends revealed. For example, if a set of attractive (synthesised) submarine designs are all nuclear powered, it is likely that 'truly' attractive designs (i.e. balanced and preferred following being fully 'worked-up') designs are also going to be nuclear-powered. A trial investigation of 'conventional' concept exploration using a set of designs on the Balanced Pareto Front would be a sensible check in exploring the robustness of the application of the NPF approach when researching a novel concept.

I.5.5 GENERATING SYSTEM GROP LEVEL PARETO FRONTS FOR PRODUCING POTENTIAL DESIGNS FROM 'SMART' SAMPLING

For expediency, in testing the second stage of the trial of the NPF approach in Chapter 7, proxy models for unrefined prospective SSH(N)s were created that were intended to substitute for the mathematical models for each SG. The proxy models of each SG represent their approximate contribution to the overall cost and 'performance' using its top-level input variable values, thus not performing the computationally expensive task of describing equipment and compartments, as options are compared against each other. Figure 37 presented a comparison between an SG proxy model and a 'real' SG-level Pareto Front, and it was concluded the adopting the proxy models for the test was justified. Preliminary studies (not presented[1]) of constructing SG-level Pareto Fronts by generating compartments and equipment have indicated that such generation is possible. It took an estimated three to four weeks for 'real' SG-level Pareto Fronts to be generated. It was concluded from this that it is suitable to use 'real' SG-level Pareto fronts when using the NPF approach to undertake the exploration of a submarine concept, such as the SSH(N). However, it is acknowledged that a recreation of the test case presented in Chapter 7 (Section 7.2) with 'real' SG-level Pareto Fronts is needed to be confirmed.

In Subsection 7.1.2, the sequence in which the pre-calculated SG-level Pareto Fronts were generated was seen to be important when generating the NPF. This is because the sequence in which SG options were selected was seen to be affected by interdependencies. The solution devised in Subsection 7.1.2 for dealing with interdependencies was to consider the selection of an SG option (e.g. a nuclear reactor in the Propulsion SG) given the selection of an interdependent SG option (e.g. a PH in the Strength SG).

[1] Due to the difficulty in presenting independent SG-level Pareto Fronts (described in Subsection 7.1.2)

It is the overall boat-level performance (using the sections of the MoTPC (see Table 16) relevant to the particular SGs) concerning the option selection of these SGs and not the individual SG option's performance. Thus, for any interdependent SG option, the composite performance of relevant interdependent SG options should be considered – not the sum of two interacting SG options in isolation. As a result, a set of SG-level Pareto Fronts for the (interdependent) SGs were generated, each taken to be dependent on the selection of a unique option on the SG-level Pareto Front of the preceding SG.

For all SGs, given they must be interdependent, some of the top-level input variables used to generate the system groups could affect multiple SGs. Thus, the specification of such a top-level input variable could be made in multiple SGs. The SG in which a given top-level input variable should be specified was seen to be preferable when it helped equalise the overall distribution of top-level input variables between the total number of SGs, as it was predicted to limit computation by minimising the number of SG options needed to be calculated. A subprogram in SUPERB could be created to analyse the top-level input variables and their relationships with each SG to generate a preferred equalised distribution. This could be applied 'generically' for submarine concept investigations using SUPERB, including concepts other than the SSH(N).

I.5.6 THE ROBUSTNESS OF THE NPF APPROACH

The reason why the two Pareto Fronts (NPF and BPF) in Figure 38 are non-coincident is that design options are discarded by the control program. These discarded design options have been geometrically generated and arranged, and then assessed as infeasible (i.e. unbalanced) by SUPERB. The two fronts in Figure 38 appear to be close. However, the small gap between the lines represents many rejected design options, as the options are very densely packed (see Figure 35). As discussed in this subsection, the distribution of potential options in Figure 35 is considered to represent the 'smart' sampling rejecting unattractive and/or infeasible design options. In the test outlined in Chapter 7, the control program typically instructed SUPERB to consider and reject 50-70 infeasible design options before identifying a valid (i.e. balanced) design option for a given cost point. Indeed, it was seen to be possible during the test outlined in Chapter 7 to instruct the control program to output to a computer screen, should a given design be accepted (i.e. balanced) or rejected. Thus, it was concluded that the NPF approach had functioned as intended, with the majority of unbalanced or Pareto-dominated designs having been eliminated from consideration using the SG-level Pareto Fronts in ‘smart’ sampling.

SSH(N) designs of potential interest, for example, such as those on any ‘knee of the curve’ on the Balanced Pareto Front (i.e. the range of submarine designs which are likely to represent the ‘best value for money’), could then be recreated in Paramarine to obtain a greater degree of confidence in the balance of these submarine designs – providing the number was small. This recreation could be achieved by inspecting and independently auditing these designs, using Paramarine’s more extensive assessment tools where appropriate to the level of design granularity produced at this design stage. This would then confirm that SUPERB has reasonably represented some novel submarine concept, to a concept level of definition and therefore, the BPF does contain balanced designs from which to conduct ‘conventional’ concept exploration. Due to the uncertainty defining cost and populating the proposed ‘performance’ metrics at the concept stage of the submarine design process, the submarines on the BPF can be considered to exist on a Pareto Front of Balanced Designs. Furthermore, those solutions ought to be close to being ‘truly’ non-dominated designs (as would be shown by a near ‘perfect’ metric for defining their costs and performances).

APPENDIX J - LIST OF PUBLICATIONS

J.1 UNDERWATER DEFENCE TECHNOLOGY (EUROPE) CONFERENCE 2013

Purton, I. M., Andrews, D. J., Mistry, A. & Kay, P., (2013a). Predicting the Scale of Smart Unmanned Underwater Vehicle Networks Provided by a Large Host Submarine, *Proc. of UDT 2013 (Europe),* Hamburg, Germany, June, 2013.

J.2 IMAREST'S ENGINE AS A WEAPON CONFERENCE 2013

Purton, I. M., Andrews, D. J., Mistry, A. & Kay, P., (2013b). Integrating Smart Unmanned Underwater Vehicle Networks with a Host Vessel. *Proc. of IMarEST Engine As A Weapon V*, Bristol, UK, July 2013.

J.3 RINA'S WARSHIP CONFERENCE 2014

Purton, I. M. & Andrews, D. J., (2014). Computer Simulated Trends in Designing a Future Unmanned Underwater Vehicle 'Mothership' Submarine. *Proc. of RINA Warship 2014: Naval Submarines and UUVs*, Bath, UK, June, 2014.

J.4 INTERNATIONAL MARINE DESIGN CONFERENCE 2015

Purton, I. M., Pawling, R. J. & Andrews, D. J., (2015). The Use of Computer Tools in Early Stage Design Concept Exploration to Explore a Novel Submarine Concept. *Proc. of IMDC 2015,* Tokyo, Japan, May 2015.